Introductory Astronomy

Week 5: Solar System(s)

Clip 1: Introduction

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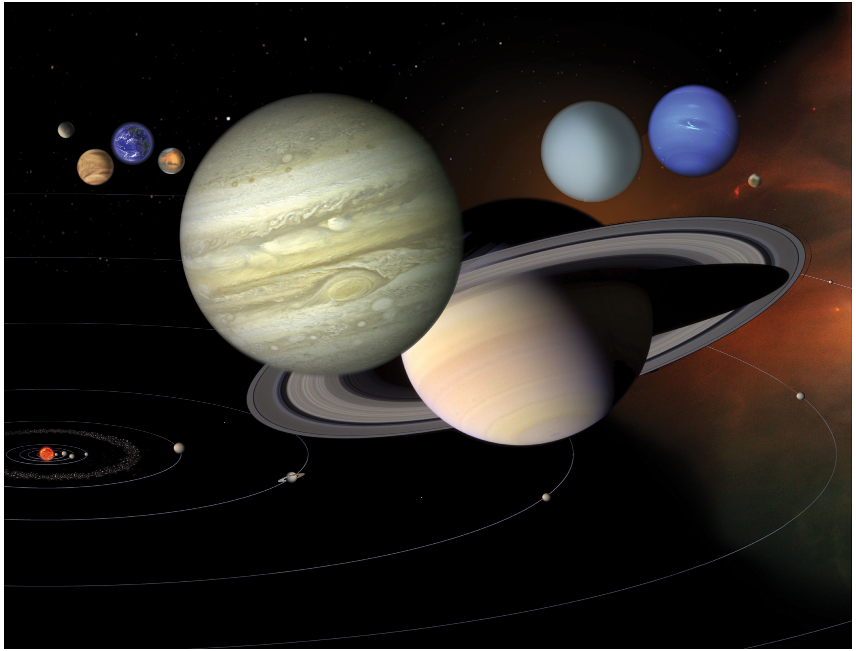
Sun

- Mostly, Solar system is an average ($1M_\odot$) main sequence star
- Sun contains about 99.9% of the bound mass
- Radiation heats planets
- Solar wind – charged particles streaming from Sun at high energy carry $1M_\oplus$ in $150My$

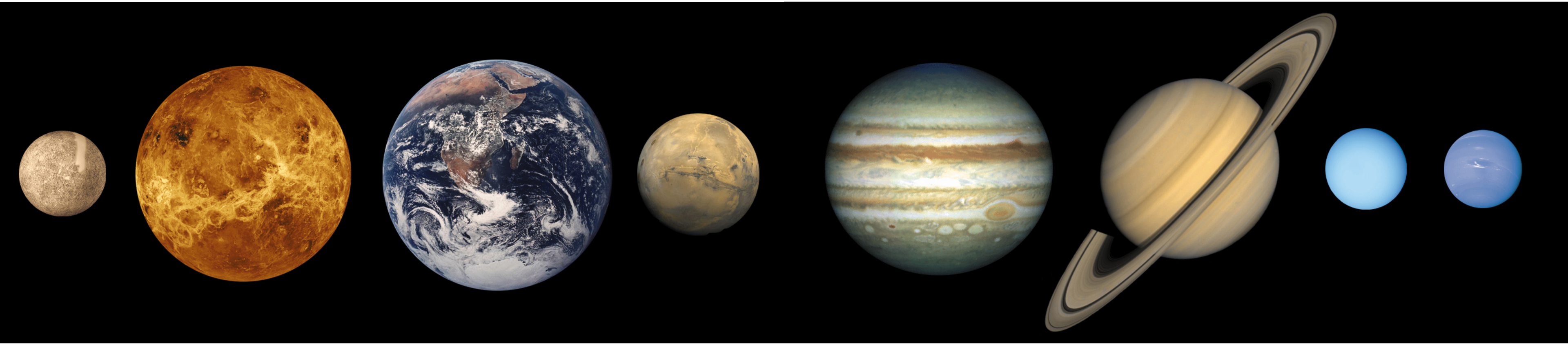
What is Out There

- Eight planets orbit Sun in slightly eccentric elliptic orbits
- Radius $0.39 - 30\ \mathrm{AU}$
- Orbits near ecliptic match Sun rotation



Two Kinds of Planets

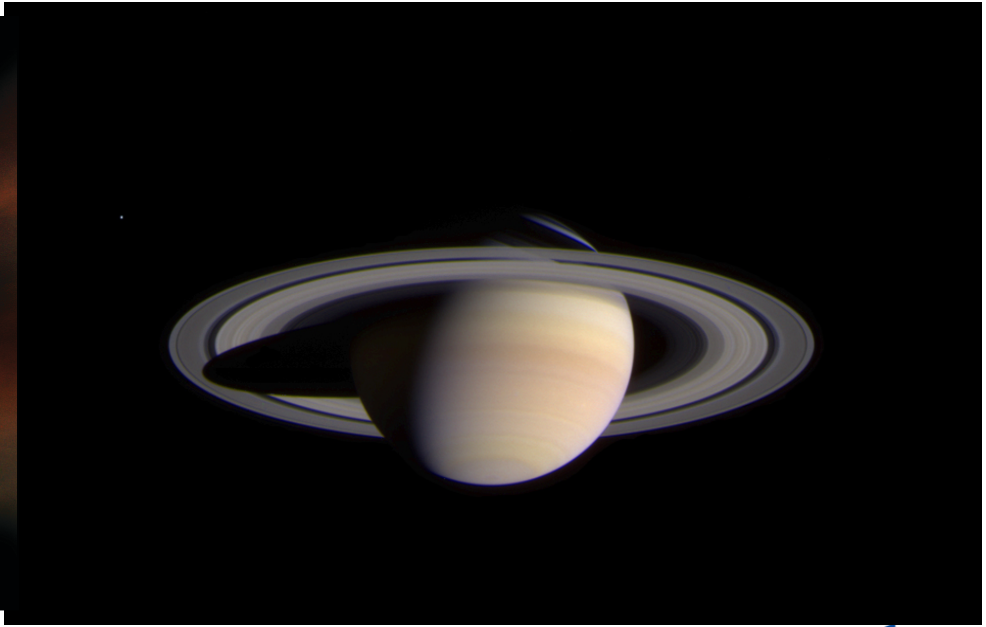
- Four Inner planets within 1.6 AU
  - Dense
  - Small
  - Rocky
- Four Outer planets from 5-30 AU
  - Less dense
  - Huge
  - Fluid



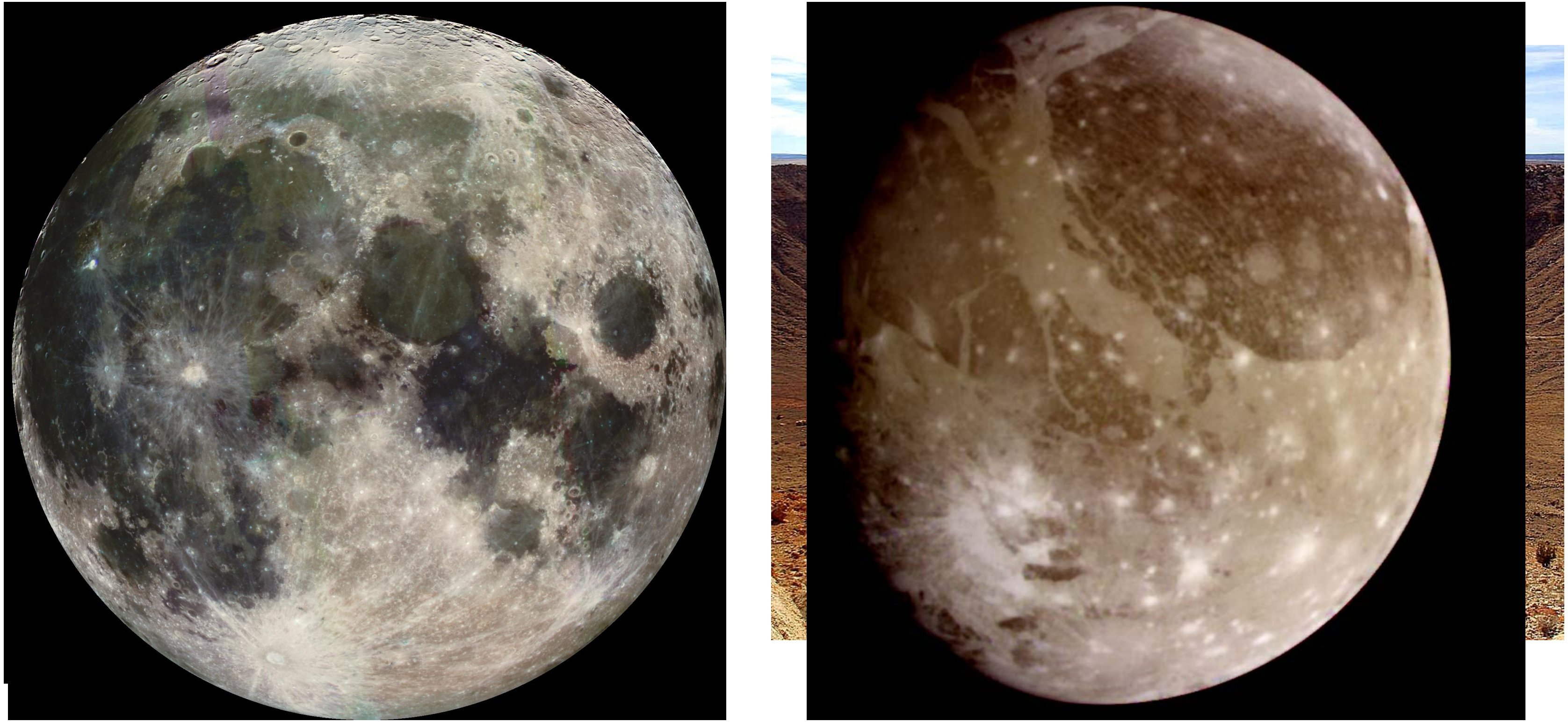
What Else?

Lots of Moons

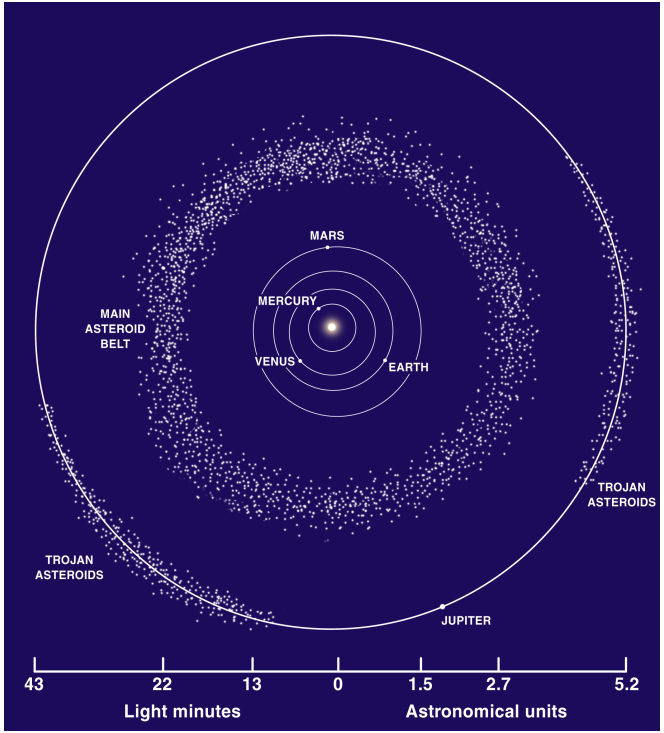
Rings

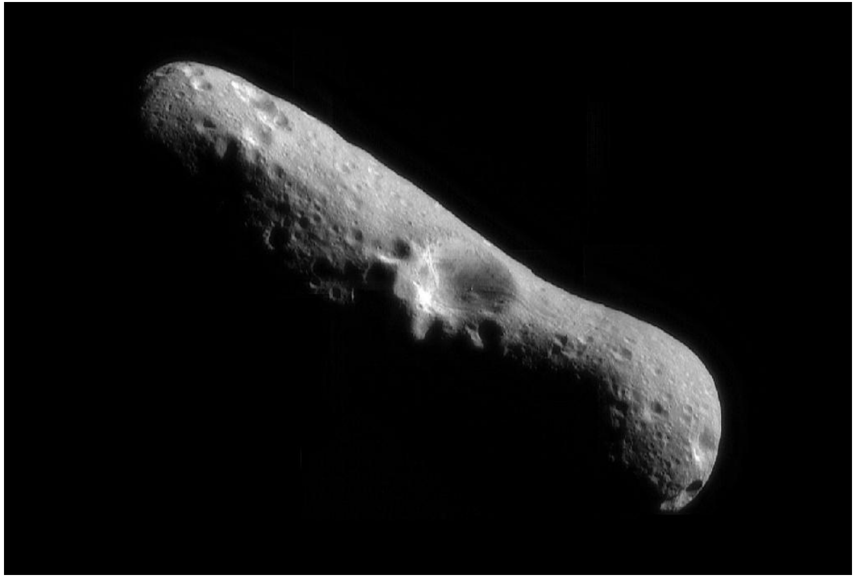


Craters

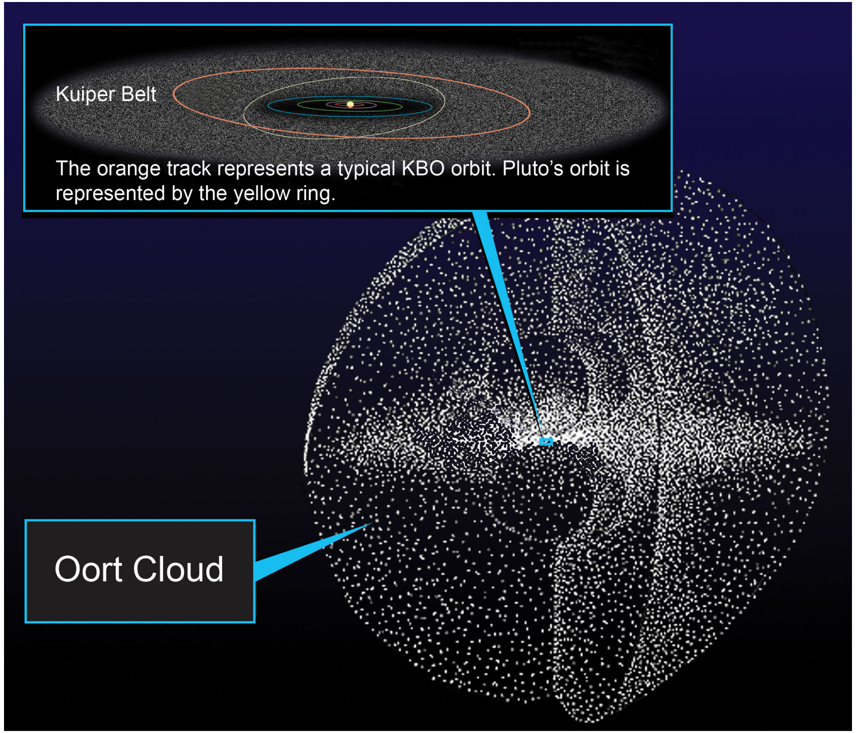


Asteroids


MARS
MERCURY
MAIN ASTEROID BELT
VENUS
EARTH
TROJAN ASTEROIDS
TROJAN ASTEROIDS
JUPITER
43
22
13
0
1.5
2.7
5.2
Light minutes
Astronomical units

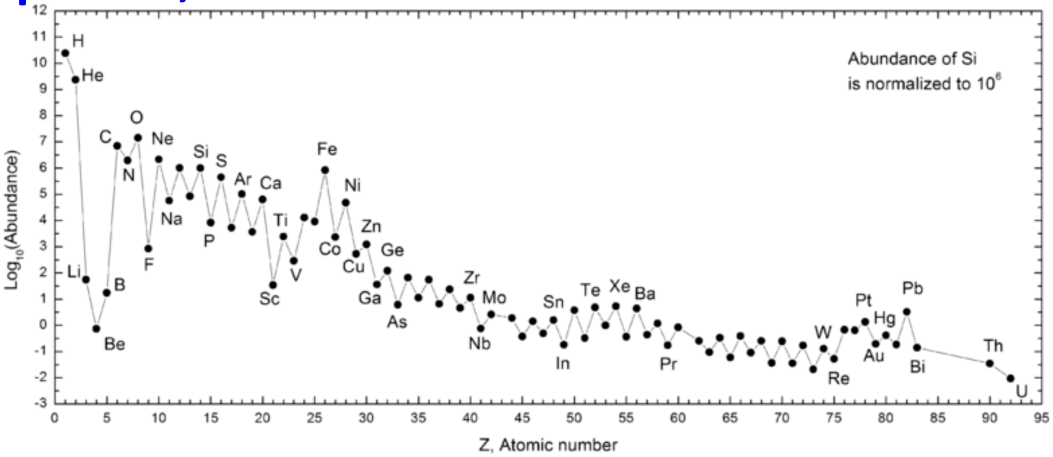


Farther Out


Kuiper Belt
The orange track represents a typical KBO orbit. Pluto's orbit is represented by the yellow ring.
Oort Cloud

What it’s Made Of

- 99.9% of mass is Sun
- 90% of rest is Jupiter, Saturn
- 70.5% Hydrogen
- 27.5% Helium
- 2% Metals



Questions

- Why are all planet orbits circular and in a plane? Why aren't comets'?
- Why are planets and large Moons round?
- Why aren't asteroids?
- Why are inner planets small, rocky, dense while outer planets are large, fluid, light?
- Why aren't asteroids a planet?
- What is the story with Pluto?
- What are rings? Why are Saturn's different?
- What made all the craters? Where did it go?
- Why do comets fall into inner Solar System? Why do asteroids fall into near-Earth orbits?
- If orbits can change – will planet orbits? Have they?
- Where did it all come from? When?

Credits

- Images : NASA/Lunar and Planetary Institute http://solarsystem.nasa.gov//multimedia/

Introductory Astronomy

Week 5: Solar System(s)

Clip 2: It’s Old

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It’s Old

- Oldest rocks on Earth are 4.4 billion years (Gy) old.
- Oldest Moon Rocks are 4.4-4.5 Gy old
- Oldest meteorite is 4.54 Gy
- Best estimate: Solar system age 4.55-4.58 Gy
- How do we know? Radioactive dating

Inside the Nucleus

- Atomic nucleus of atomic number Z and atomic mass A contains Z positive protons (Hydrogen nuclei, Rutherford 1917) and $A - Z$ neutral neutrons (Chadwick 1932)
- Nuclei with same Z but different A form chemically indistinguishable isotopes

Nuclear Decay

- Most combinations are unstable and decay via
  - α decay: emission of Helium nucleus $(Z, A) = (2, 4)$
  - β decay: emission of electron with conversion $\mathrm{n} \rightarrow \mathrm{p}$ or positron with conversion $\mathrm{p} \rightarrow \mathrm{n}$
  - Fission: breakup into two smaller nuclei
  - Accompanied in general by γ rays
- Alchemy achieved – but lead often product

Uses of Radioactivity

- Helium does not stick around. At temperatures in upper atmosphere $\langle\frac{mv^2}{2}\rangle = \frac{3}{2}kT$ means $v \sim v_{\text{escape}}$ Helium on Earth today is the product of α-decay
- Radioactive decay is a source of internal heat

Radiometric Dating

- Radioactive decay is random statistical process. Time in which half a sample decays is property of isotope – half-life

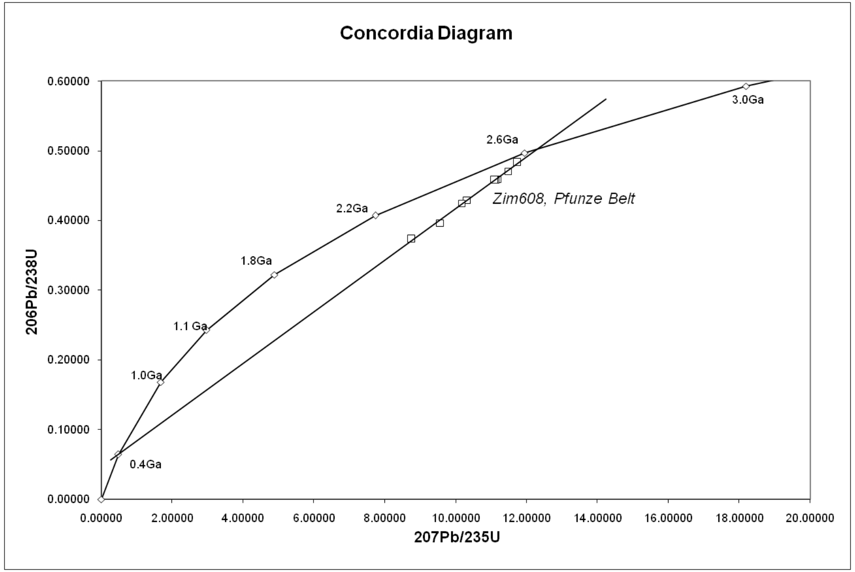
$$N(t) = 2^{-t/t_{1/2}} N(0)$$

- With time, daughter concentration increases while parent concentration decreases
- If we find a case where daughter escapes liquid magma but is trapped in solid rock, then

$$N_D/N_P(t) = 2^{t/t_{1/2}} - 1$$

Using the Method

- Zircon binds Uranium but not Lead
- Two isotopes of Uranium produce two isotopes of lead providing cross-check



Credits

- Concordia diagram, as used in U-Pb dating, with data from the Pfunze Belt, Zimbabwe. Diagram own work using data points from: Vinyu, M.L., Hanson, R.E., Martin, M.W., Bowring, S.A., Jelsma, H.A. and Dirks, P.H.G.M. 2001. U-Pb zircon ages from a craton-margin Archaean orogenic belt in northern Zimbabwe. Journal of African Earth Sciences, 32, 103-114. http://en.wikipedia.org/wiki/File:Pfunze_belt_concordia.png

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Week 5: Solar System(s)

Clip 3: The Solar Nebula

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In the Beginning

- Solar System begins in molecular cloud
- Fragmentation and Gravitational Collapse triggered by nearby Supernova?
- Fragment of size 2000-20,000 AU mass $3000 M_\odot$
- Sun likely member of open cluster now dispersed

- Denser regions within cloud collapse when gravity overcomes pressure
- Jeans instability

$$k_B T \sim \frac{GMm}{R}$$

Making a Cluster

Density

Temperature

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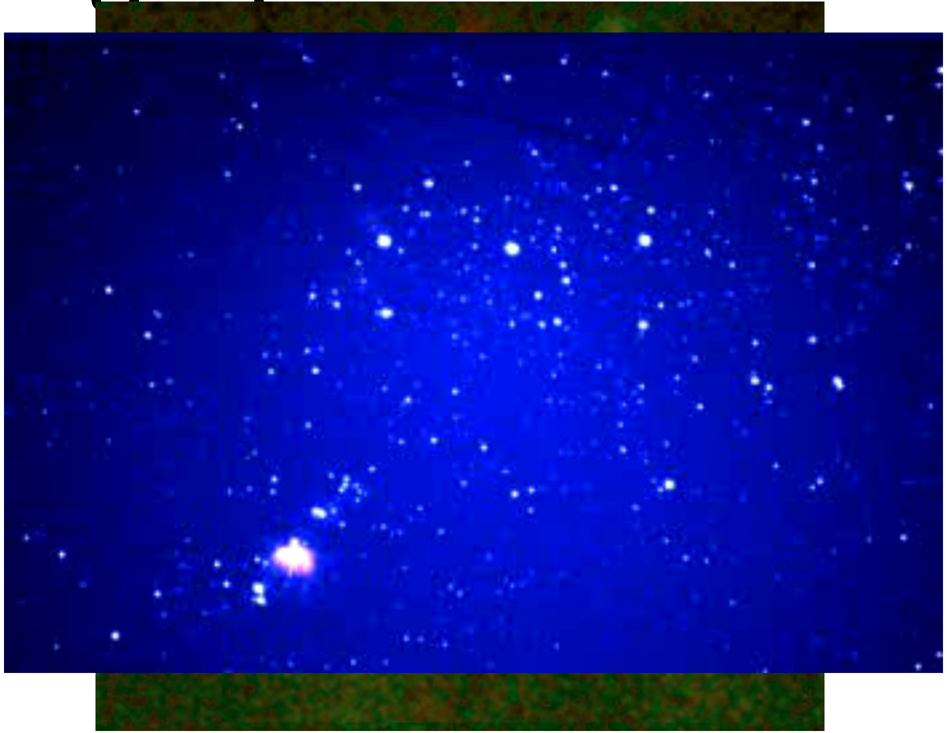
Spinning Up

- Collapse speeds up initial rotation
- Collapse in plane inhibited by centrifugal barrier
- Nebula flattens into protoplanetary disk of radius $\sim 200\,\mathrm{AU}$ within 100Ky

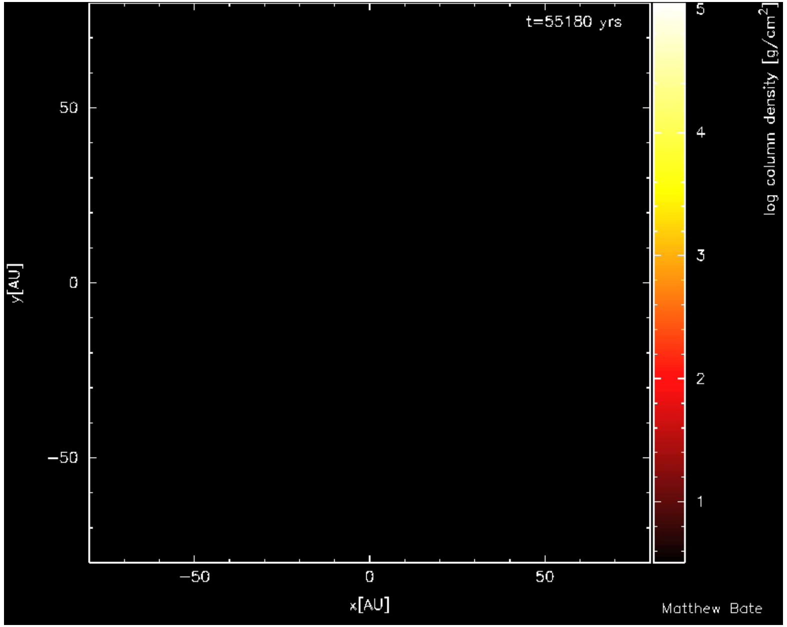


Heating Up

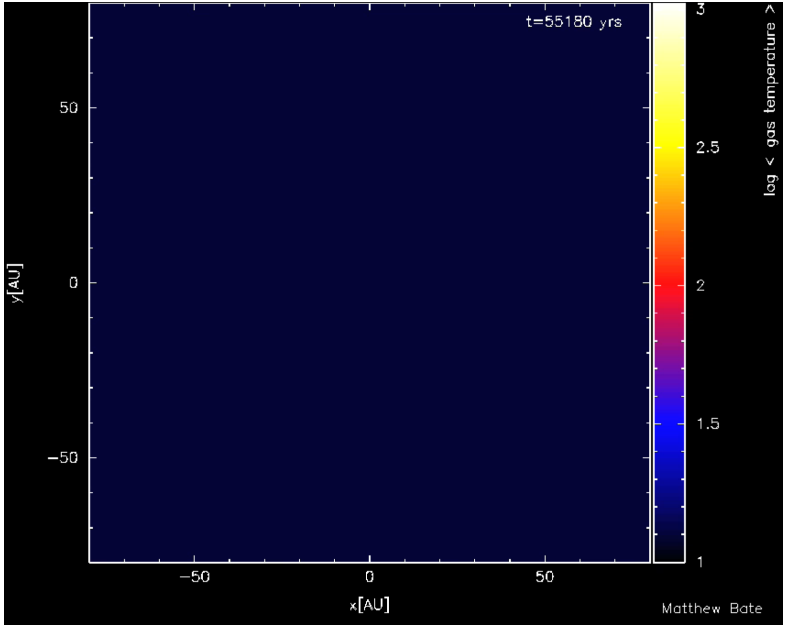
- Friction converts gravitational potential energy into heat (Kelvin-Helmholtz)
- Temperature and density highest in center
- Protosun surface temperature 2000 K
- Disk contains Hydrogen, Helium, trace metals in molecular form
- In 10My T-Tauri wind blows away gas and dust

Making a Star

Column Density



Temperature



Credits

- Astronomy Animations: University of Nebraska-Lincoln Astronomy Education Group http://astro.unl.edu/
- Concordia diagram, as used in U-Pb dating, with data from the Pfunze Belt, Zimbabwe. Diagram own work using data points from: Vinyu, M.L., Hanson, R.E., Martin, M.W., Bowring, S.A., Jelsma, H.A. and Dirks, P.H.G.M. 2001. U-Pb zircon ages from a craton-margin Archaean orogenic belt in northern Zimbabwe. Journal of African Earth Sciences, 32, 103-114. http://en.wikipedia.org/wiki/File:Pfunze_belt_concordia.png
- HH-30 Image: NASA/STScI http://hubblesite.org/newscenter/archive/releases/1995/24/image/e/
- Cluster and Protostellar Disk Animation: Professor Matthew Bate, University of Exeter, UK http://www.astro.ex.ac.uk/people/mbate/Animations/
- Demonstration Video: Duke Media Services

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Week 5: Solar System(s)

Clip 4: Terrestrial Planet Formation

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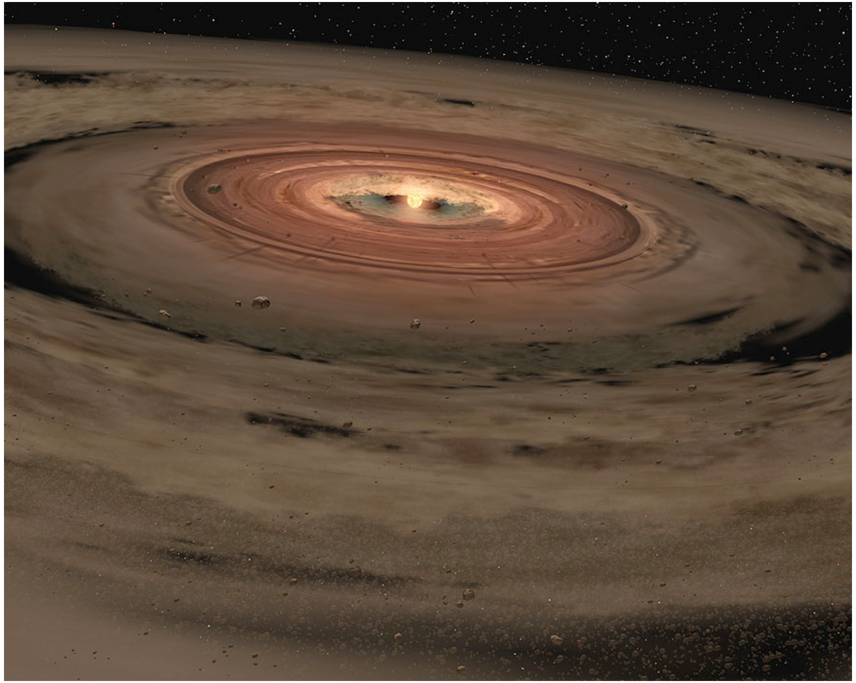
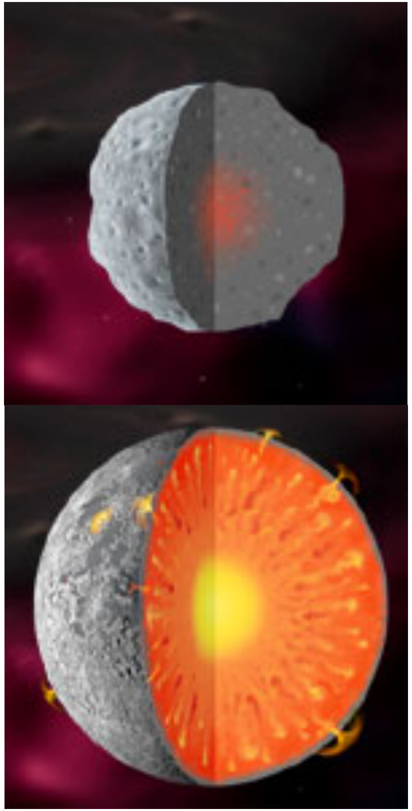
Dust to Planetesimals

- Grains of dust (solids) collide and adhere
- Larger grains grow to 10^9 planetesimals of size 1km - gravitationally bound
- Keplerian orbits sweep through dust
- Gravitational interaction increasingly important, growth rate ~R^4 for 100Ky



Protoplanets

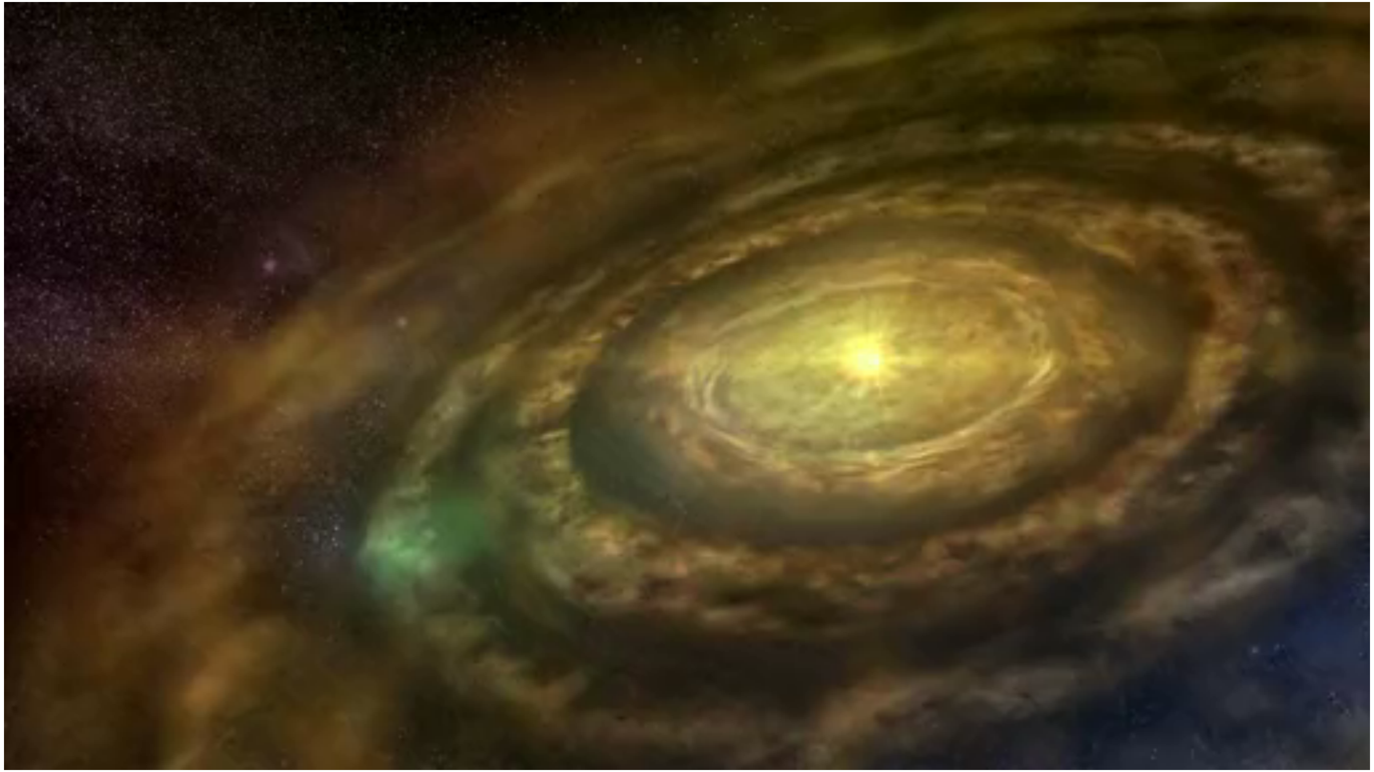
- Form hundreds of protoplanets R≤1000km
- Heat of collisions along with radioactivity melts protoplanets
  - Objects this large are spheres: no mountains in the ocean
  - Chemical differentiation: heavier material sinks to core
- Gravity opposed by pressure gradient
- Compression heats core



A Live Protoplanet

Planets

- Larger protoplanets accrete remaining planetesimals
- End with 100 Moon-Mars sized protoplanets in cleared gaps in disk
- Gravitational interactions distort orbits
- Remaining planetesimals ejected
- Collisions lead to merger or ejection leaving large Venus and Earth
- Mercury stripped to core
- Mars does not grow
- Orbits settle to near-circular in 10-100My



Credits

- 51 Ophiuchi Disk: NASA/JPL-Caltech/T. Pyle (SSC) http://www.nasa.gov/centers/goddard/news/topstory/2009/dust_disks.html
- Chemical Differentiation: Smithsonian Museum of Natural History: The Dynamic Earth http://www.mnh.si.edu/earth/text/5_1_4_0.html
- Vesta Rotation: NASA/Dawn Mission http://www.nasa.gov/multimedia/videogallery/index.html?collection_id=65362&media_id=152548561
- Planet formation animation: NASA/University of Copenhagen/Lars Buchhave http://www.nasa.gov/multimedia/videogallery/index.html?collection_id=14471&media_id=146251701

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Week 5: Solar System(s)

Clip 5: Beyond the Snow Line: Giants

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The Rich Life

- Beyond the snow line solids include water (5AU) and methane (30AU) so more prevalent
- Planetesimal and protoplanet formation much faster especially near snow line
- Jupiter grows fastest, reaching $10 - 15 M_{\oplus}$ with rocky core and watery mantle

Giants

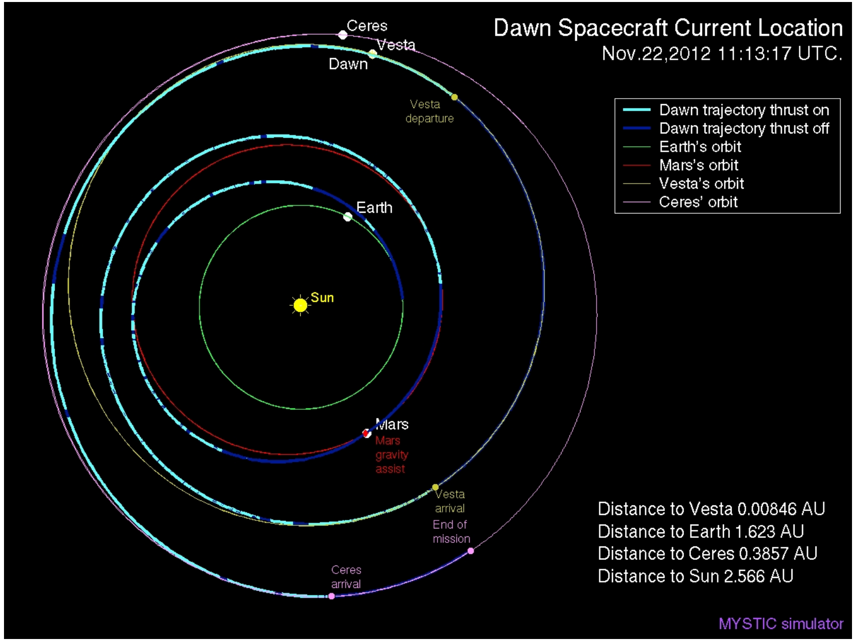
- Once core can bind gas (H_2,He) - grows rapidly until gas in orbit exhausted – 10My
- Core forms accretion disk as gas collapses: protostar at smaller scale – leftovers here are moons and rings
- Saturn farther out starts later, less gas

More Giants?

- What about ice giants Uranus and Neptune?
- At present location would not grow in time
- Likely formed closer in and migrated out
- Later start – only $\sim M_\oplus$ of H_2

Changing Orbits?

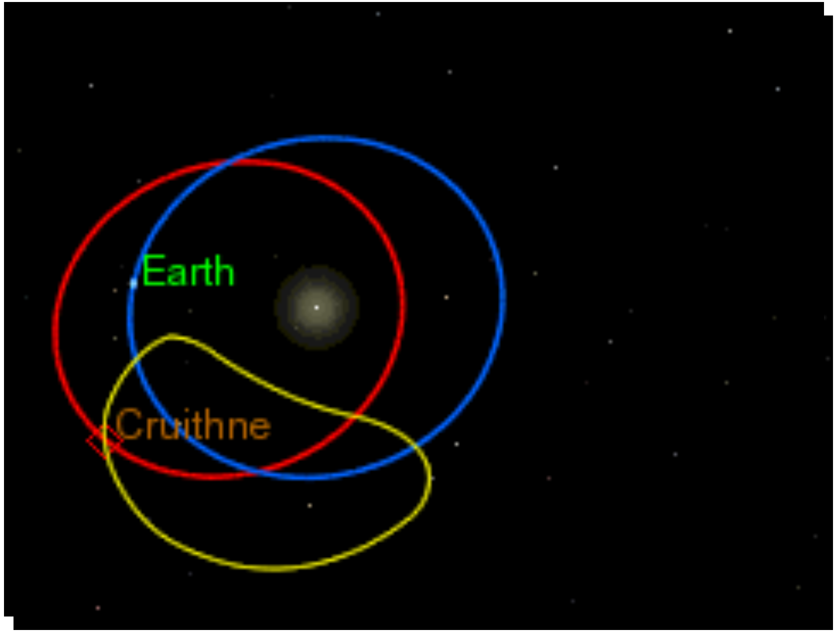
- Newtonian two-body physics is freshman exercise
- Three-body problem unsolvable, chaotic
- Can think of lighter objects as perturbing orbits about most massive
- Near a planet a spacecraft or planetesimal goes into a hyperbolic scattering orbit
- After scattering off moving planet it goes into a new Solar orbit



Orbital Resonance

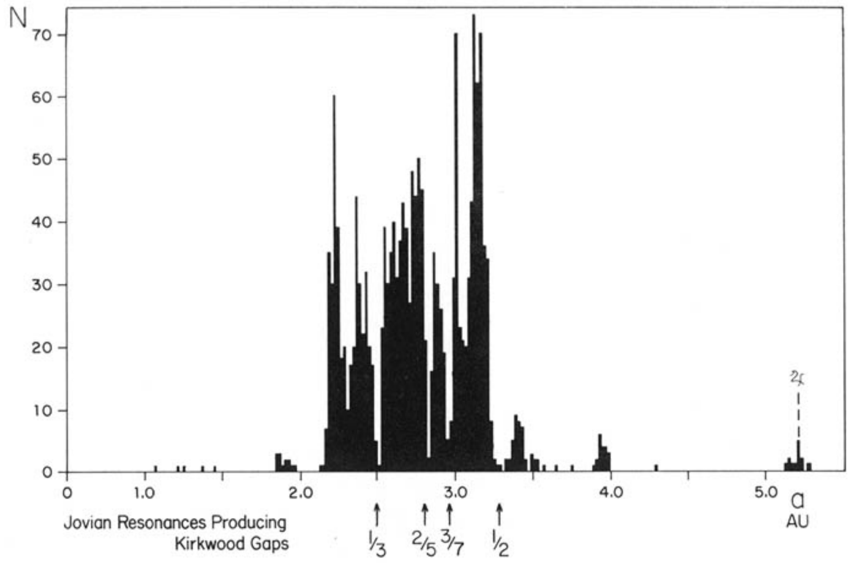
- From a distance gravitational interaction perturbs orbit slightly
- If periods of Solar orbits of two objects are resonant perturbation is commensurate with orbit
- Successive perturbations add
- Can get (meta-)stable resonances
- More frequently resonance destabilizes orbit

Our Other Moon



The Asteroid Belt

- 2-4AU out, planet formation disrupted by resonances with Jupiter (and Saturn)
- Orbits near resonance perturbed, creating more violent destructive collisions
- Some material ejected completely – resonant orbits unstable



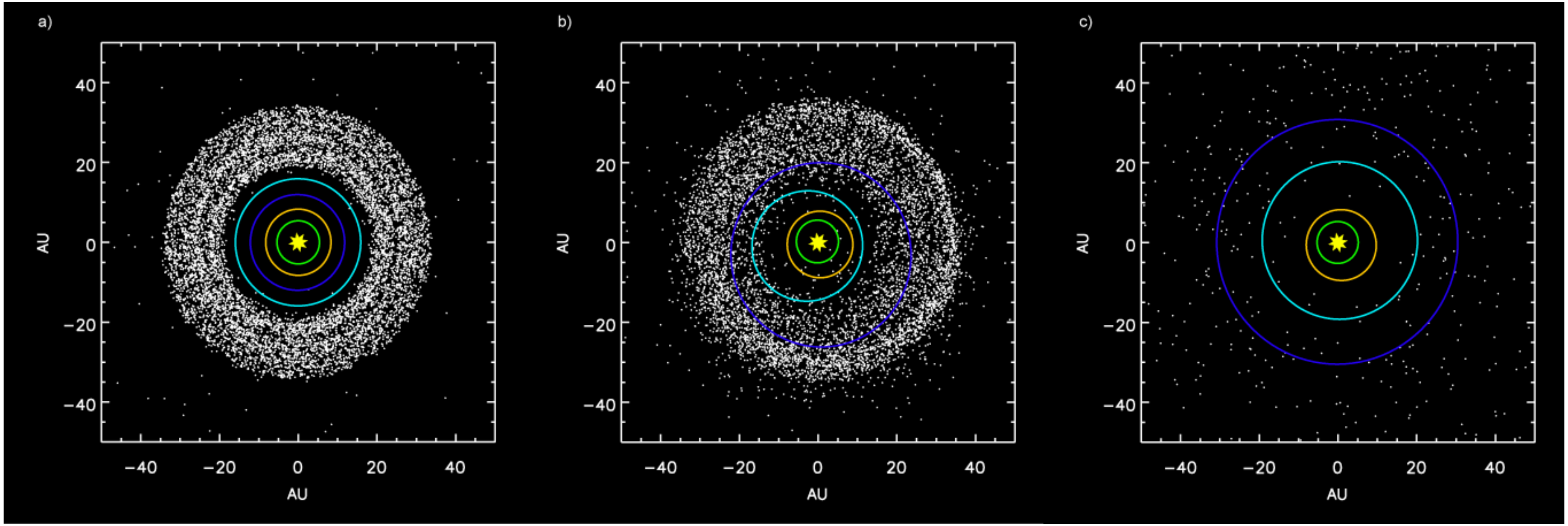
Moving Out – the Nice Model

- Four giants form 5.5-17AU from Sun exhausting disk
- Beyond this orbit, $35M_\oplus$ of icy planetesimals to 35AU
- Collisions slow fragments, shift giants slowly out over a few My
- Motion brings Jupiter and Saturn into 2:1 resonance after 600My drawing both into eccentric orbits and destabilizing system
- The joint resonance further depletes asteroid belt

More Niceness

- Saturn moves out, encountering Uranus and Neptune pushing them into eccentric orbits
- Here they encounter planetesimals destroying disk
- Some planetesimals scattered into higher orbits – Trans-Neptunian Objects
- Others slowed into inner Solar system creating heavy bombardment
- Remnants of disk create friction settling giants into current stable, nearly circular orbits

The Nice Model



Questions

- Why are all planet orbits circular and in a plane? Why aren't comets'? ✔
- Why are planets and large Moons round? ✔
- Why aren't asteroids? ✔
- Why are inner planets small, rocky, dense while outer planets are large, fluid, light? ✔
- Why aren't asteroids a planet? ✔
- What is the story with Pluto?
- Why do some planets have magnetic fields and others not?
- What are rings? Why are Saturn's different?
- What made all the craters? Where did it go?
- Why do comets fall into inner Solar System? Why do asteroids fall into near-Earth orbits?
- If orbits can change – will planet orbits? Have they? ✔✗
- Where did it all come from? When? ✔

Summary: Timeline

- 0: Supernova(e?) triggers collapse 4.56Bya
- 100Ky: Planetesimals
- 10My: Outer planets have formed

  Protoplanets in inner system

  T-tauri winds sweep away gas and dust
- 100My: Inner planets and Moon form
- 600My: Jupiter Saturn resonance. Outer planets migrate, asteroid belt depleted, heavy bombardment
- 700My: Current stable configuration. First life on Earth

Credits

- Astronomy Animations: University of Nebraska-Lincoln Astronomy Education Group http://astro.unl.edu/
- Cruithne: Wikimedia Commons http://en.wikipedia.org/wiki/3753_Cruithne
- Dawn Trajectory: NASA/JPL http://dawn.jpl.nasa.gov/mission/live_shots.asp
- Kirkwood Gaps: NASA/JPL http://history.nasa.gov/SP-345/p56.htm
- Nice Model: Wikimedia Commons http://commons.wikimedia.org/wiki/File:Lhborbits.png

Introductory Astronomy

Week 5: Solar System(s)

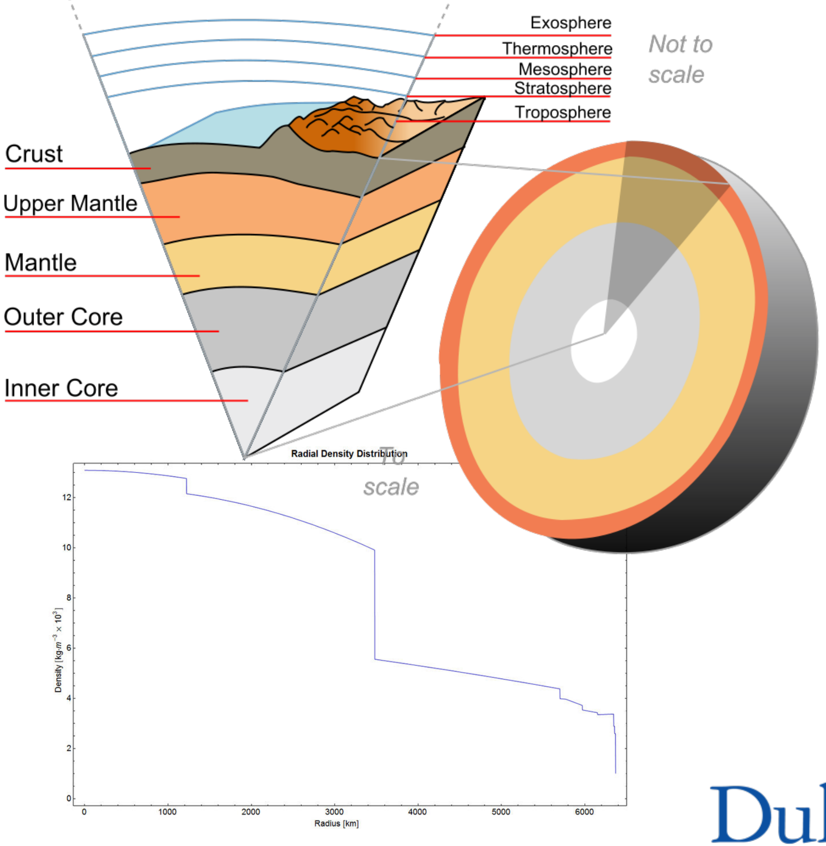
Clip 6: Earth is a Planet

On the Surface

- 71% of Earth covered with water
- Above this is atmosphere of (mostly) N_2, O_2
- Surface is rocky (Si) crust

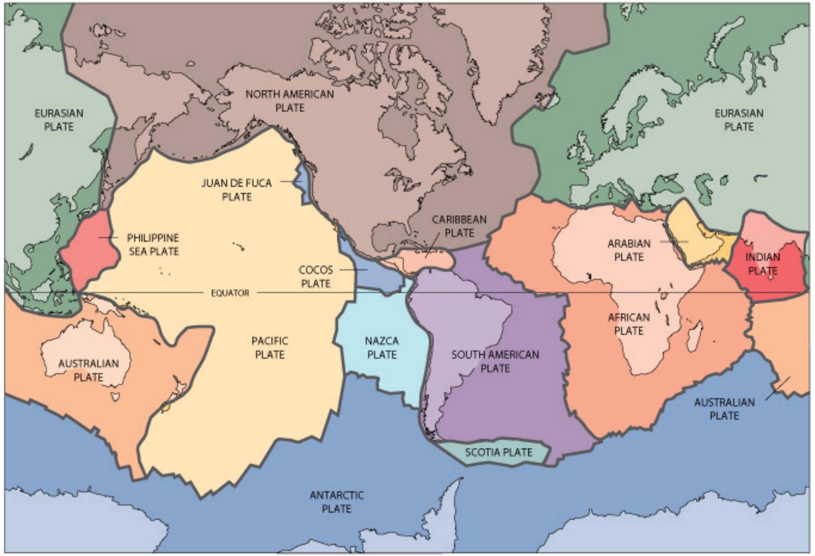
Inside Earth

- In molten Earth chemical differentiation. Fe, Ni rich core, Si crust and mantle
- Density 5500 kg/m^3
- Pressure, density, temperature increase with depth
- Internal structure studied via seismology



Internal Heat

- Heat generated in interior by
  - Radioactive decay
  - Kelvin-Helmholtz
- Drives convection in mantle
- Crust broken into plates dragged by mantle
- Heat loss $87\,\mathrm{W/m^2}$



Energy Balance

- Surface temperature nearly constant
- Absorb energy as radiation from Sun, with small contribution from internal heat
- Lose energy by radiation to space
- In equilibrium, these rates are equal

If Earth were Black

$$I_{\text{in}} = b_{\odot}\pi R_{\oplus}^{2} = \frac{1}{4}L_{\odot}\left(\frac{R_{\oplus}}{D_{\odot}}\right)^{2} = \pi R_{\oplus}^{2}\sigma T_{\odot}^{4}\left(\frac{R_{\odot}}{D_{\odot}}\right)^{2}$$

$$I_{\text{out}} = 4\pi R_{\oplus}^{2}F = 4\pi R_{\oplus}^{2}\sigma T_{\oplus}^{4}$$

- Set them equal

$$T_{\oplus} = T_{\odot}\left(\frac{R_{\odot}}{2D_{\odot}}\right)^{1/2} = 279\,\mathrm{K}$$

It’s Blue?

- Earth reflects about $a = 0.306$ of the radiation
- This fraction is Earth’s albedo
- So

$$I_{\text{abs}} = (1 - a) I_{\text{in}}$$

- Hence

$$T_{\oplus} = (1 - a)^{1/4} T_{\odot} \left(\frac{R_{\odot}}{2D_{\odot}} \right)^{1/2} = 254\,\mathrm{K}$$

Credits

- Earth: NASA http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=9643
- Earth Interior: Wikimedia Commons http://en.wikipedia.org/wiki/File:Earth-crust-cutaway-english.svg
- Earth Density: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Mantle Convection: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Plates: USGS http://pubs.usgs.gov/publications/text/slabs.html
- Energy Budget : NASA Educational Materials http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Earths_Energy_Budget.html
- Global Winds: NOAA http://www.srh.noaa.gov/jetstream/global/circ.htm
- Magnetic Field Schematics: USGS http://www.usgs.gov/faq/index.php?action=artikel&cat=11&id=477&artlang=en
- Magnetic Field Model: Dr. Gary A. Glatzmaier - Los Alamos National Laboratory - U.S. Department of Energy http://www.es.ucsc.edu/~glatz/geodynamo.html
- Radiation Belts: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Magnetosphere Animation: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Aurora: NASA/UC Berkeley http://www.nasa.gov/vision/universe/solarsystem/aurora1110.html

Introductory Astronomy

Week 5: Solar System(s)

Clip 7: Our Moon

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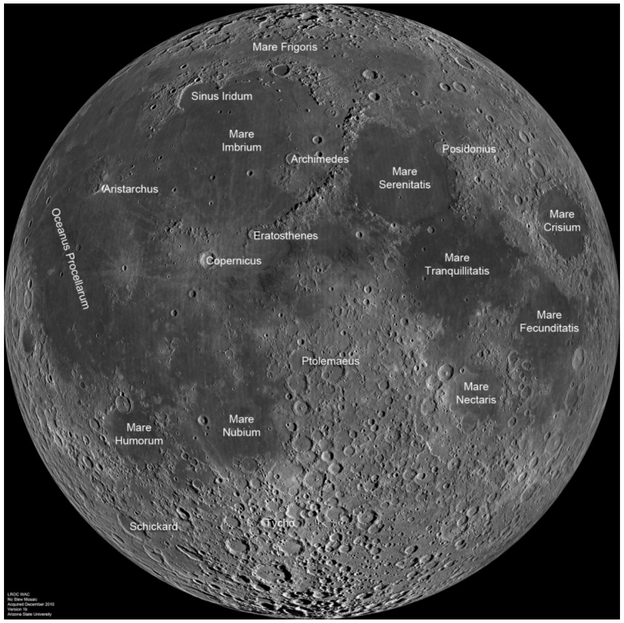
We’ve Been There!

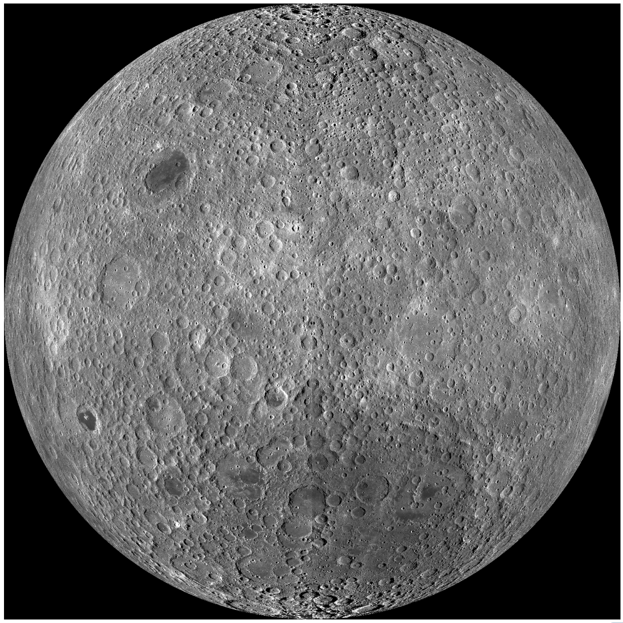
- 12 humans have visited the Moon
- Brought back samples
- Left experiments
- What have we learned?

What we see

Nearside: Maria, Craters



Farside: Craters, no Maria

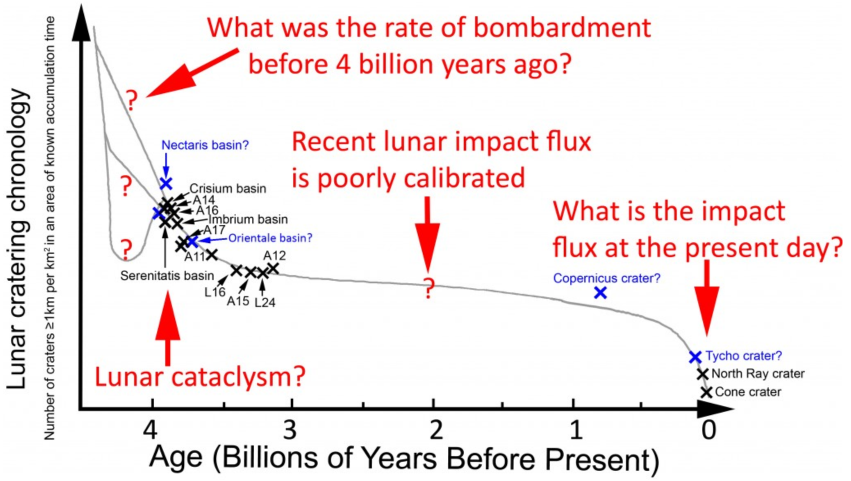


Surface

- Craters created by impacts
- Maria are lava plains often filling old craters
- Rilles and Graben result from shrinking of interior
- No current volcanism. Small planets cool faster
- (Almost) No atmosphere. Molecules photodissociated by UV and lost to space
- Temperature 370K day 100K night
- No water. Ice in crater shadows 35K
- Crust is old weathered by impacts to regolith
- Lunar surface is a museum of history

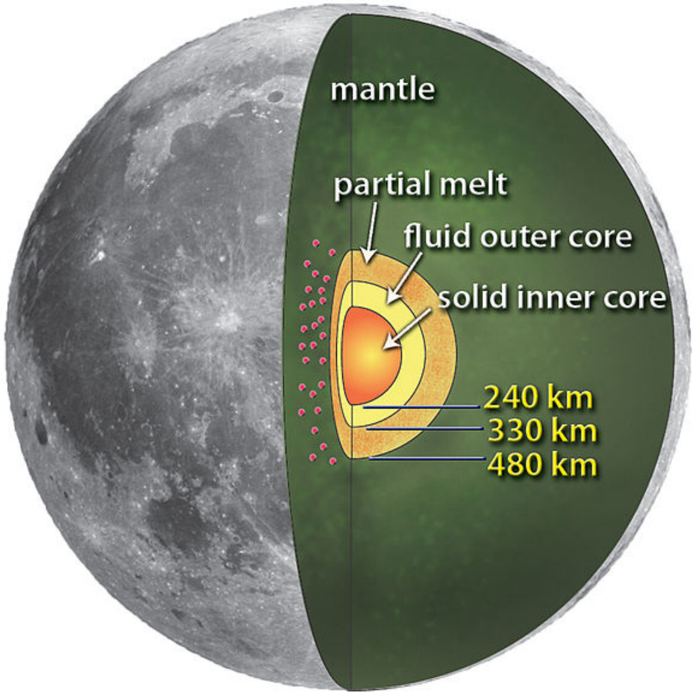
History

- Combining crater dating with radiometric dating of lunar samples and meteorites leads to history of bombardment rates



Inside

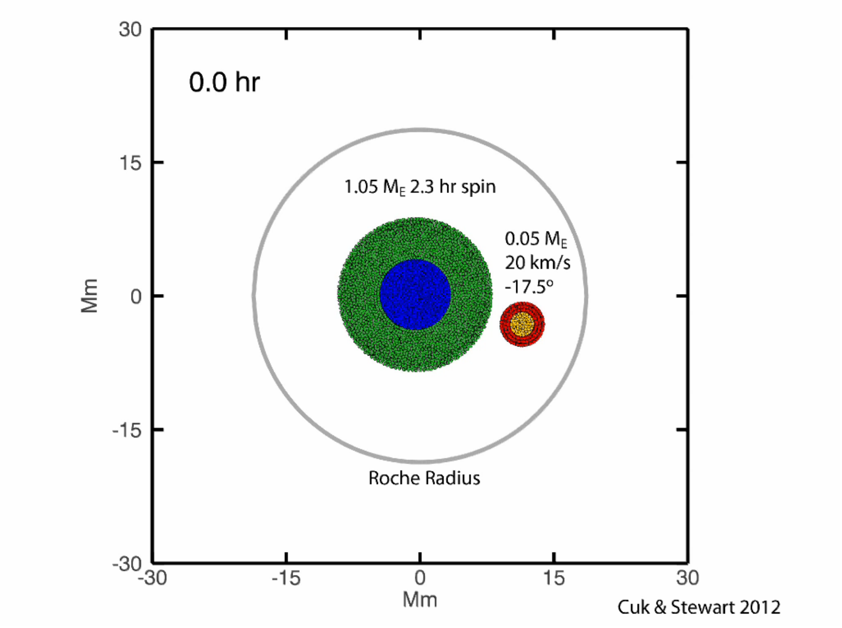
- Chemical differentiation produced core mantle
- Lunar core is small
- Moonquakes caused by Earth's tidal forces
- No geodynamo



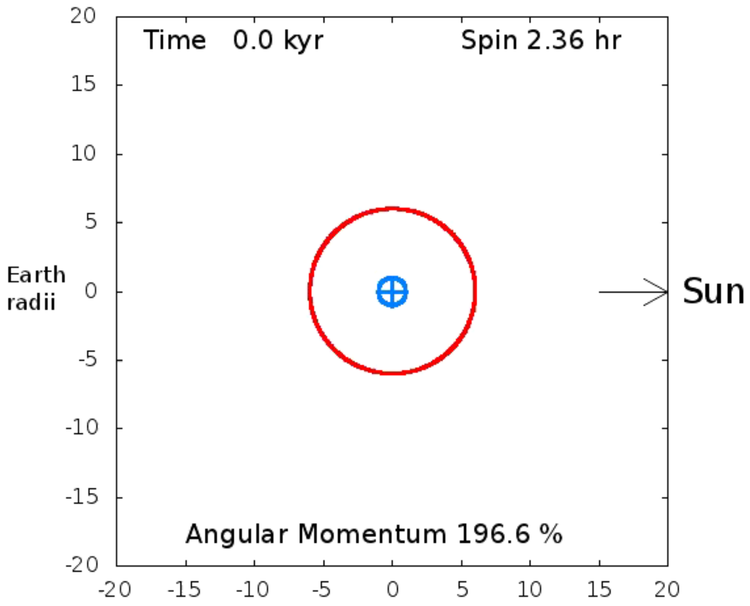
Where did Moon Come From?

- Mineral Composition of Moon very close to Earth minus core
- Large satellite compared to Earth
- Orbit tilt anomalously large
- Likely produced in giant impact early in Earth history
- Moon formed from iron-poor debris $R \sim 23,000\,\mathrm{km}$
- Earth left with 5h day
- Tidal effects slow Earth, boost Moon away

Recent Simulations



Cuk & Stewart 2012



Credits

- Lunar Images: NASA http://www.hq.nasa.gov/alsj/a11/images11.html#Mag40
- Lunar Impact Rates: MoonZoo/K. Joy http://blog.moonzoo.org/2011/02/21/big-bangs-in-the-solar-system/
- Moon Formation Simulations: S. Stewart http://www.fas.harvard.edu/~planets/sstewart/Moon.html

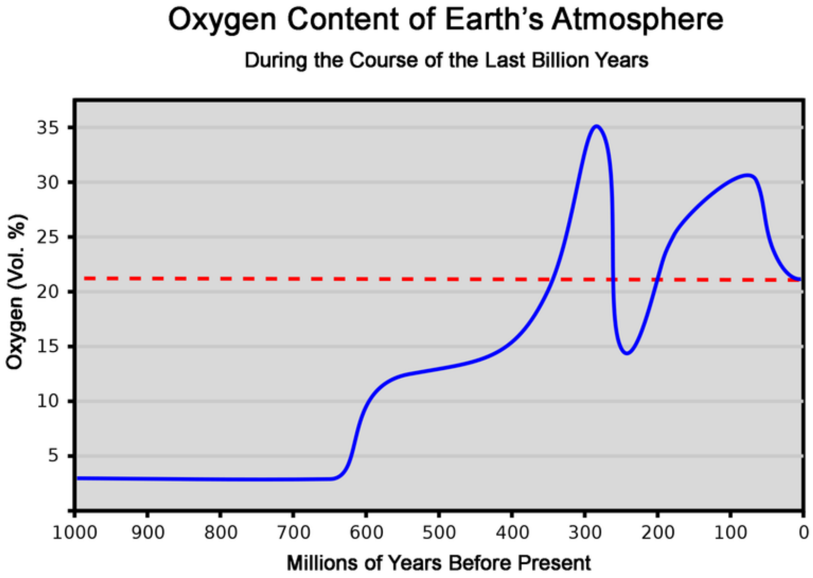
Introductory Astronomy

Week 5: Solar System(s)

Clip 8: The Atmosphere and Beyond

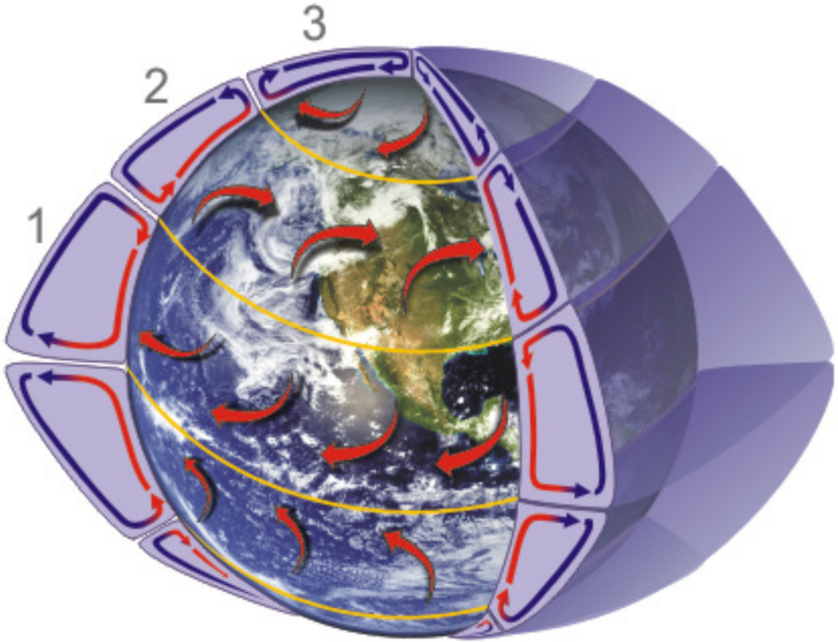
Atmosphere?

- Where did gases and water come from?
- N_2, CO_2 released from minerals in volcanic outgassing
- H_2O imported from outer system during heavy bombardment
- Rain creates oceans which dissolve CO_2 and fix it in sediments – accelerated by emergence of continents
- Bacteria, plants release O_2 initially taken up by Fe, S



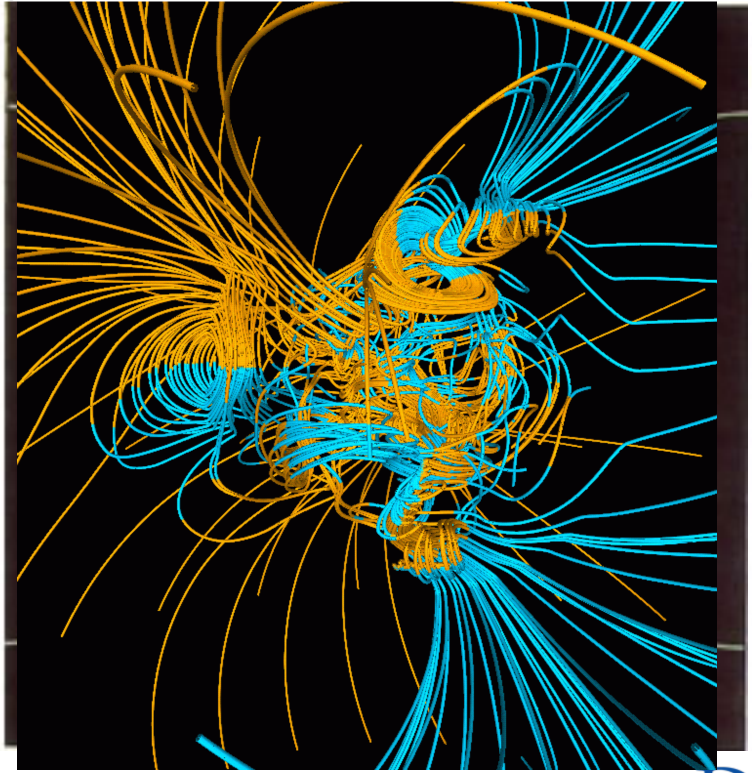
Atmospheric Physics

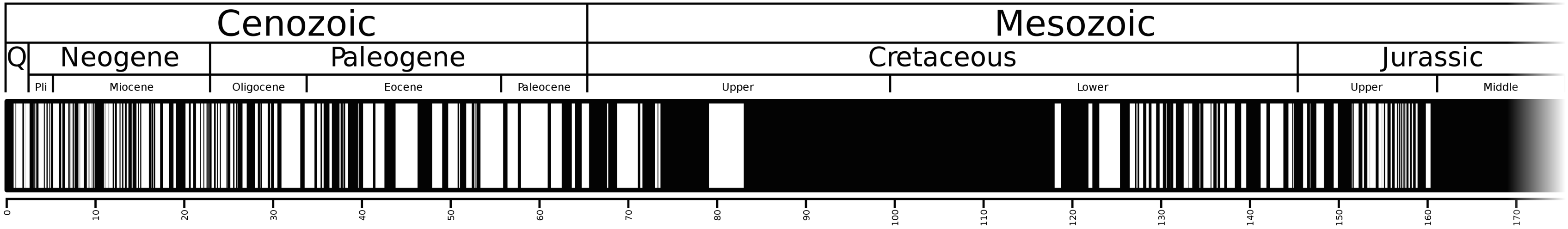
- Heated surface heats lower atmosphere driving convection
- Differential heating guides convection cells
- Rotation twists vertical motion to global winds



Earth Magnetism

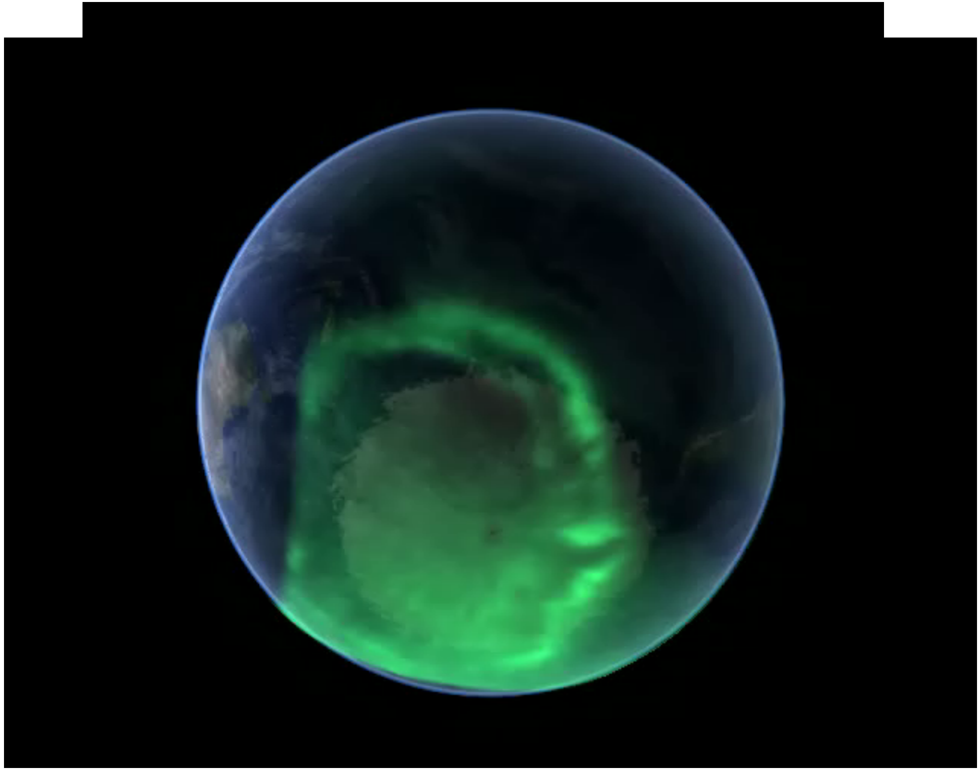
- Earth is a magnet roughly aligned with rotation axis
- Dynamo: convective flow of conducting outer core powered by heat of core and ongoing chemical differentiation and directed by rotation
- Field reverses polarity unpredictably




Cenozoic
Mesozoic
Q
Neogene
Paleogene
Cretaceous
Jurassic
Pli
Miocene
Oligocene
Eocene
Paleocene
Upper
Lower
Upper
Middle
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170

What the Field Does

- Charged particles of Solar wind trapped by field lines into radiation belts
- Solar wind deforms field
- During Solar storms some particles break through to atmosphere – visible by ionization



Summary

- Features of Earth as a planet we know well can serve as benchmarks for comparison
  - Tectonics/Geological Activity
  - Atmosphere/Temperature
  - Magnetic Field
- Atmospherically and geologically active Earth erases past.

Credits

- Earth: NASA http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=9643
- Earth Interior: Wikimedia Commons http://en.wikipedia.org/wiki/File:Earth-crust-cutaway-english.svg
- Earth Density: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Mantle Convection: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Plates: USGS http://pubs.usgs.gov/publications/text/slabs.html
- Energy Budget : NASA Educational Materials http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Earths_Energy_Budget.html
- Global Winds: NOAA http://www.srh.noaa.gov/jetstream/global/circ.htm
- Magnetic Field Schematics: USGS http://www.usgs.gov/faq/index.php?action=artikel&cat=11&id=477&artlang=en
- Magnetic Field Model: Dr. Gary A. Glatzmaier - Los Alamos National Laboratory - U.S. Department of Energy http://www.es.ucsc.edu/~glatz/geodynamo.html
- Radiation Belts: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Magnetosphere Animation: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Aurora: NASA/UC Berkeley http://www.nasa.gov/vision/universe/solarsystem/aurora1110.html

Introductory Astronomy

Week 5: Solar System(s)

Clip 9: The Greenhouse Effect

The Greenhouse Effect

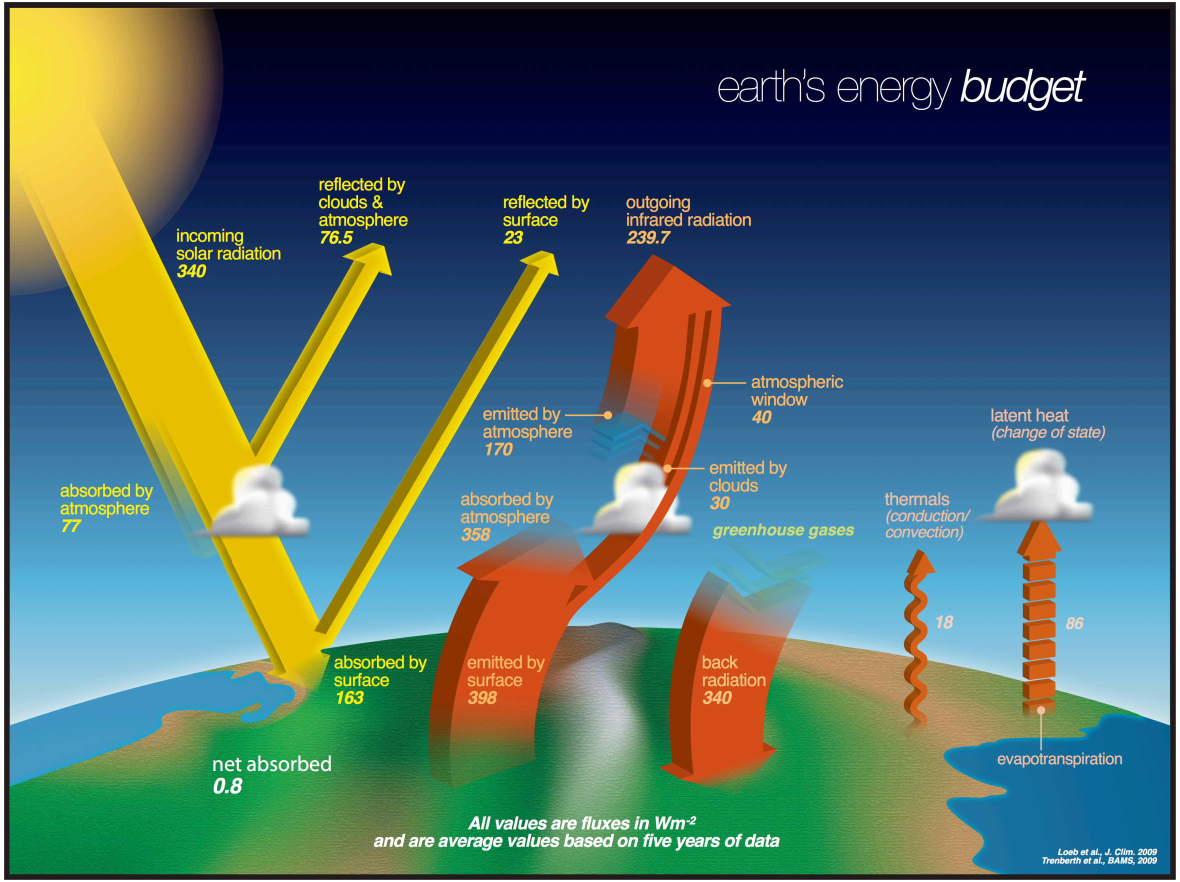
- Incoming Sunlight (visible) absorbed by surface through transparent atmosphere
- Radiated light (infrared) absorbed by molecules in atmosphere, heating this.
- Absorbed heat reradiated
- Surface warmer than equivalent blackbody

A Simple Model

- If atmosphere ideally transparent to V and absorbs a fraction g of IR
- Surface and atmosphere in equilibrium

- Surface $\sigma T_\oplus^4 = \sigma T_A^4 + F_{\rm in}$
- Atmosphere $2\sigma T_A^4 = g\sigma T_\oplus^4$

$$(1-g/2)\sigma T_\oplus^4 = F_{\rm in} \quad T_\oplus = (1-g/2)^{-1/4} T_{\rm no\,gh}$$



earth's energy budget

***All values are fluxes in Wm^{-2}
and are average values based on five years of data***

Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009

More Greenhouse Effect

- We found $T_\oplus = T_\odot \left(\frac{1-a}{1-g/2} \right)^{1/4} \left(\frac{R_\odot}{2D_\odot} \right)^{1/2}$
- With $a = 0.306,\ g = 0.85$ we find $T_\oplus = 292K$
- Atmospheric greenhouse effect crucial to making Earth inhabitable
- Changes in a, g can alter climate drastically

Credits

- Earth: NASA http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=9643
- Earth Interior: Wikimedia Commons http://en.wikipedia.org/wiki/File:Earth-crust-cutaway-english.svg
- Earth Density: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Mantle Convection: Wikimedia Commons http://en.wikipedia.org/wiki/File:RadialDensityPREM.jpg
- Plates: USGS http://pubs.usgs.gov/publications/text/slabs.html
- Energy Budget : NASA Educational Materials http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Earths_Energy_Budget.html
- Global Winds: NOAA http://www.srh.noaa.gov/jetstream/global/circ.htm
- Magnetic Field Schematics: USGS http://www.usgs.gov/faq/index.php?action=artikel&cat=11&id=477&artlang=en
- Magnetic Field Model: Dr. Gary A. Glatzmaier - Los Alamos National Laboratory - U.S. Department of Energy http://www.es.ucsc.edu/~glatz/geodynamo.html
- Radiation Belts: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Magnetosphere Animation: NASA/T. Benesch, J. Carns http://www.nasa.gov/mission_pages/rbsp/news/electric-atmosphere.html
- Aurora: NASA/UC Berkeley http://www.nasa.gov/vision/universe/solarsystem/aurora1110.html

Introductory Astronomy

Week 5: Solar System(s)

Clip 10: Terrestrial Planets

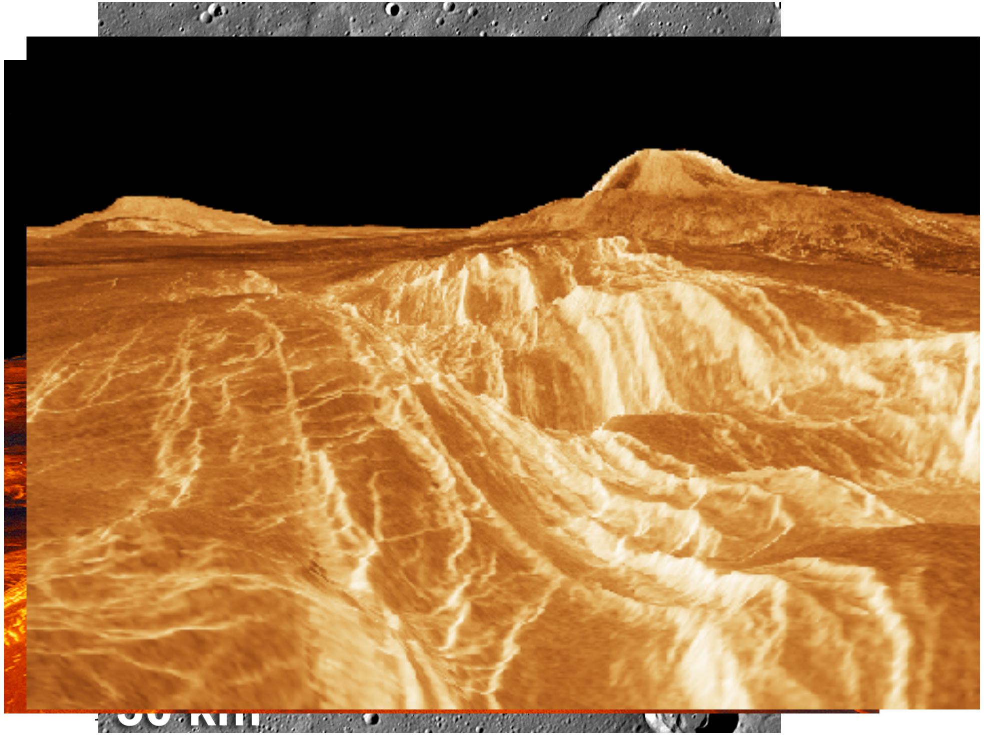
Spin and Orbit

- Mercury: close to Sun and eccentric: 3:2 tidal locking to 88d orbit tilted 7°
- Venus: 224d orbit tilted 3.4°; 243d retrograde spin tilted 177.3°
- Mars: 687d orbit tilted 1.9°; 24.6h spin tilted 25°

On the Surface

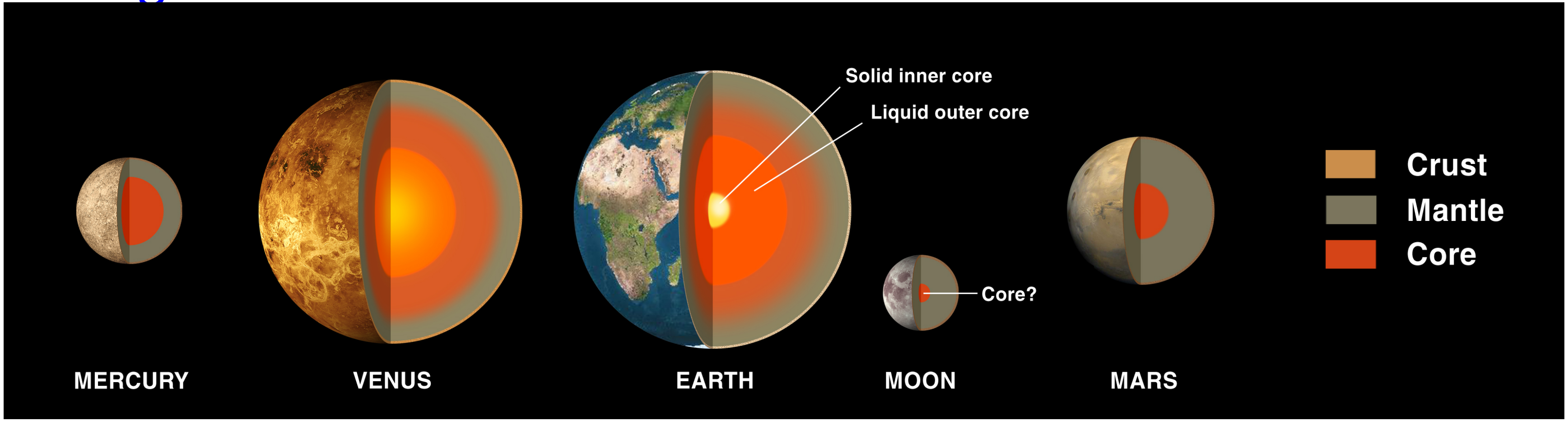
Tectonic Activity:

- Mercury: Features reflect cooling compression and extension
- Venus: Strong flaky crust and viscous mantle. Tesserae, chasmate. Global Resurfacing 400Mya
- Mars: Two Plates?
- Evidence of volcanic activity on Mars extinct



Inside

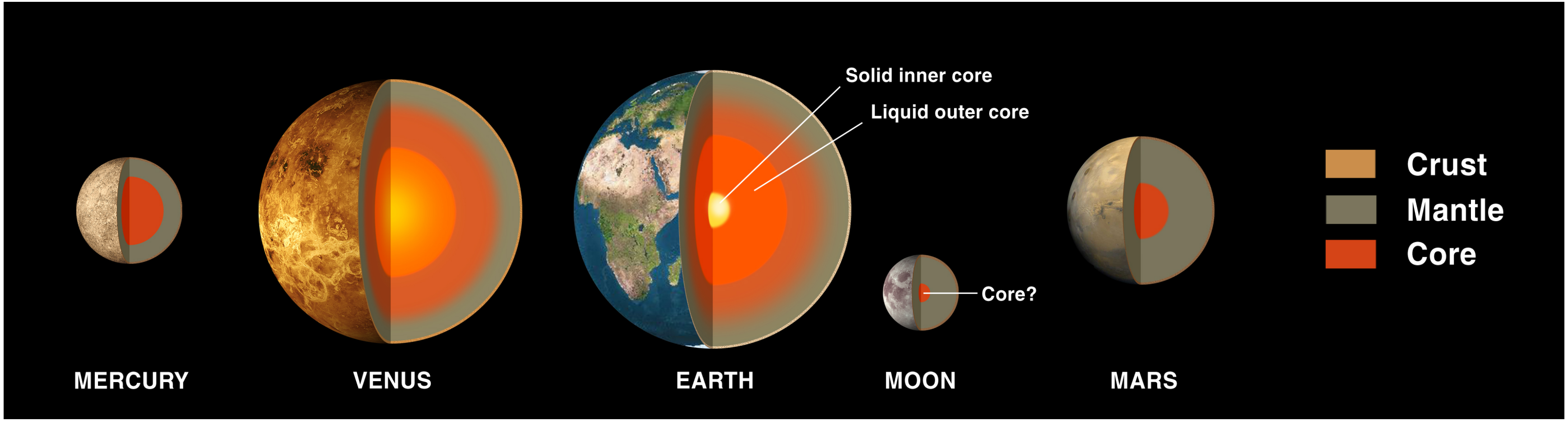
Mercury: Relatively huge core: uncompressed density $5300\,\mathrm{kg}/\mathrm{m}^3$, at least partially liquid. Dipolar Magnetic Field



Inside

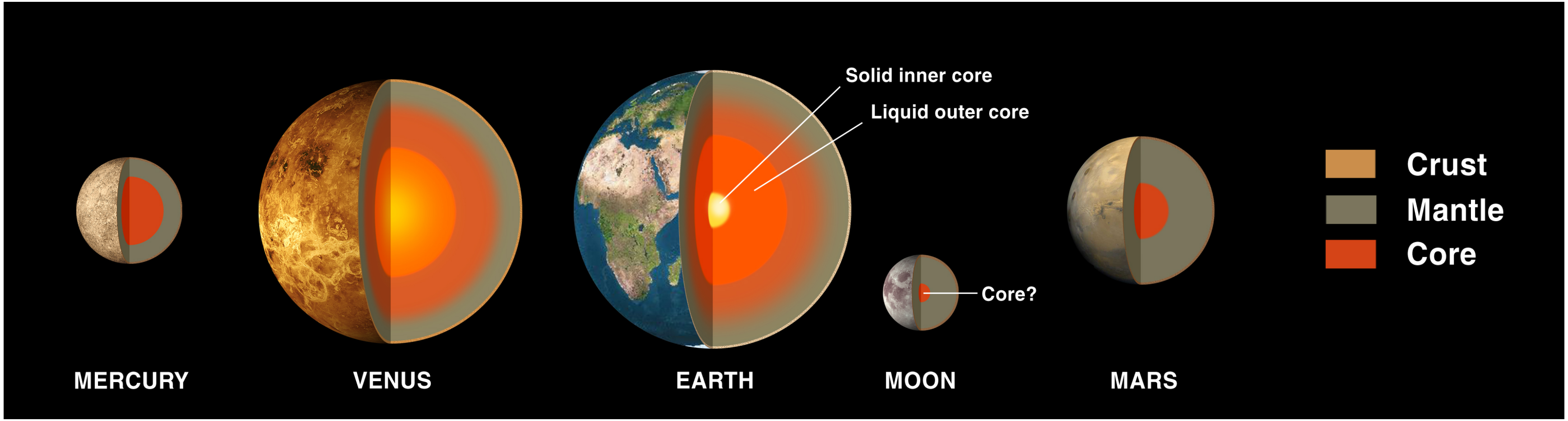
Venus: Presumed similar to Earth, density $5243\,\mathrm{kg/m^3}$

No geodynamic Magnetic Field



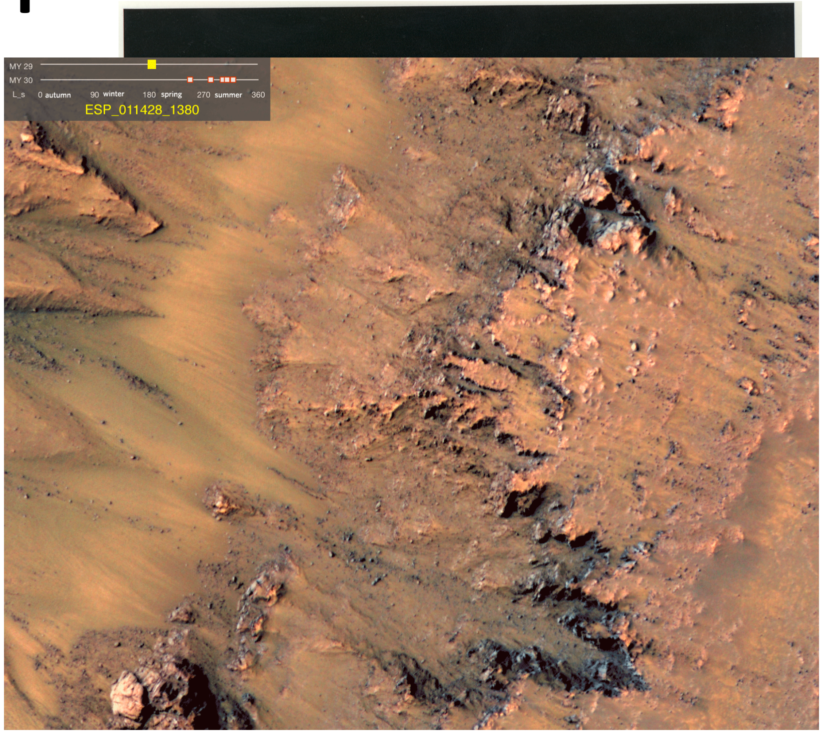
Inside

Mars: Small core, density$3934\,\mathrm{kg/m^3}$ Mantle inactive. No Magnetic Field now but old geodynamo



Atmospheres

- Mercury: Not much. Albedo 0.142 T=700K/100K. Ice in shadows?
- Venus: Dense (93x Earth) CO_2. SO_2 clouds Albedo 0.9 T=730K No water.
- Mars: Tenuous (.005x Earth) CO_2. Albedo 0.25 T= 308/130 seasonal. Large polar ice caps. Water?



Why? A Comparative History

- Venus: Initially similar to Earth. CO_2 outgassed and water
- Evaporating water does not condense - dissociated and H_2 lost
- No oceans or tectonics CO_2 builds up
- Runaway greenhouse

- Mars: Initially similar to Earth. CO_2 outgassed and water
- Evaporating water condenses and rains, removing greenhouse gases
- No tectonics, gas trapped in rocks stays there
- Cooling traps water as permafrost if not lost to dissociation
- Weak magnetic field allows Solar Wind to strip remnant atmosphere
- Runaway Icehouse

Credits

- Mercury Orbit Animation: NASA JHU/APL http://sciencenetlinks.com/interactives/messenger/or/OrbitRotation.html
- Mercury Surface: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/Watters_Press_photo_1.jpeg
- Venus Surface Image: NASA/JPL http://www2.jpl.nasa.gov/magellan/image13.html
- Mars: NASA http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=2050
- Mars Topography: NASA http://photojournal.jpl.nasa.gov/jpeg/PIA02031.jpg
- Internal Structure: NASA http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=168
- HD 17255 Animation: NASA/JPL-Caltech http://www.nasa.gov/mission_pages/spitzer/multimedia/spitzer-20090810.html
- Venus Clouds: NASA http://nssdc.gsfc.nasa.gov/image/planetary/venus/pvo_uv_790205.jpg
- Mars Icecap: Philip James (University of Toledo), Steven Lee (University of Colorado), NASA http://nssdc.gsfc.nasa.gov/image/planetary/mars/hst_mars060.jpg
- Water on Mars: NASA/JPL-Caltech/Univ. of Arizona http://www.nasa.gov/mission_pages/MRO/news/mro20110804.html

Introductory Astronomy

Week 5: Solar System(s)

Clip 11: Giant Planets

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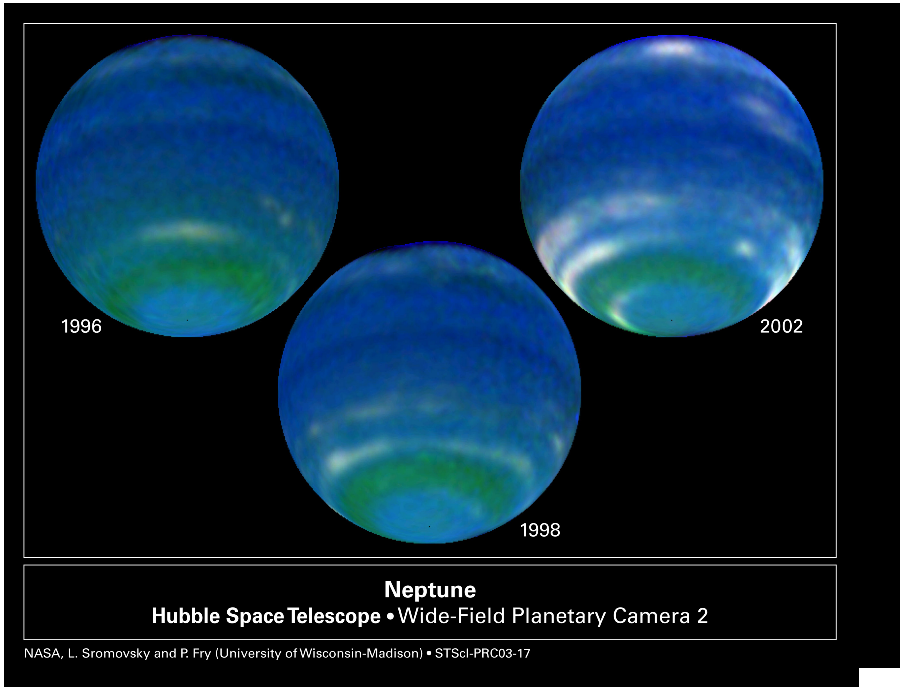
Spin and Orbit

- Jupiter: 11.9y orbit inclined 1.3°; 9.9h differential spin inclined 3.1°
- Saturn: 29.5y orbit inclined 2.5°; 10.6h differential spin inclined 26.7°
- Uranus: 84.3y orbit inclined 0.8°; 17.2h spin tilted 97.8°
- Neptune: 164.8y orbit inclined 1.8°; 16.1h spin tilted 28.3°

Surface - Atmosphere

- H_2 He atmosphere is all we see
- Uranus, Neptune blue due to trace methane
- Heating from interior drives convection
- Rapid rotation creates global winds with storms at boundaries

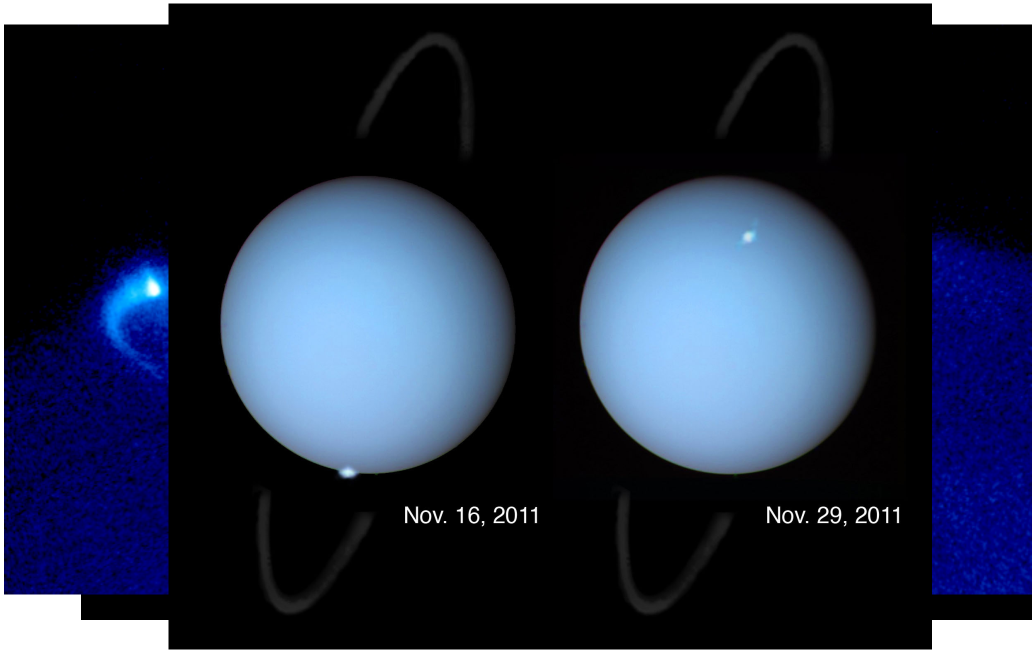


Neptune
Hubble Space Telescope • Wide-Field Planetary Camera 2

NASA, L. Sromovsky and P. Fry (University of Wisconsin-Madison) • STScI-PRC03-17

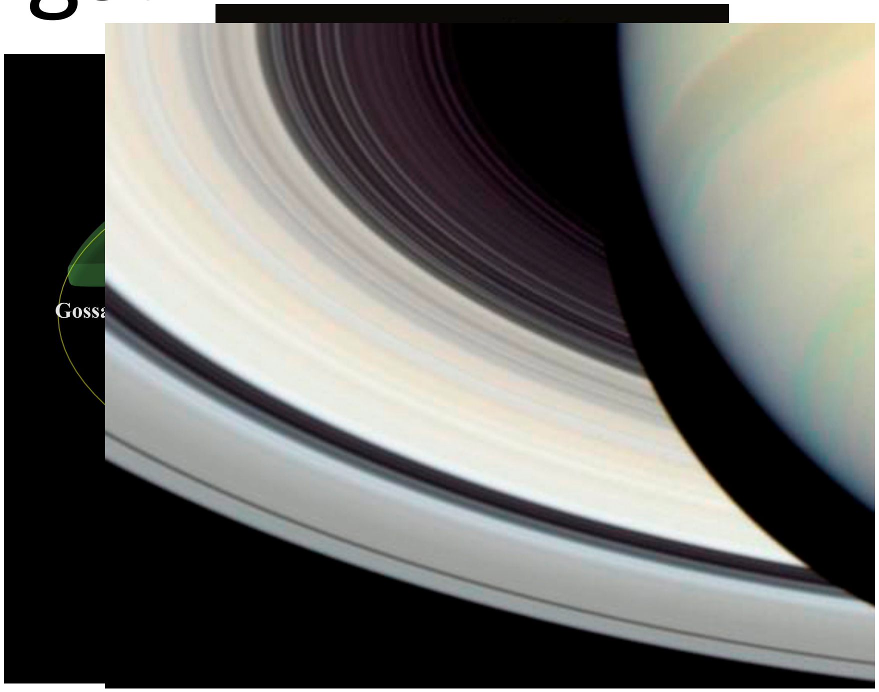
Inside

- Compressed-Earth-like core conjectured from oblateness
- Metallic H mantle – strong magnetic dipole
- Ice mantle – magnetic field tilted offset
- Internal heat from Kelvin-Helmholtz significant



Rings!

- Jovian planets form by gravitational instability in nebula and collapse to accretion disk
- Near planet, tidal forces prevent gravitational accretion of light matter leaving ring structures
- Saturn's rings brilliant made of ice



Roche (1848) Limit

- Roche Limit

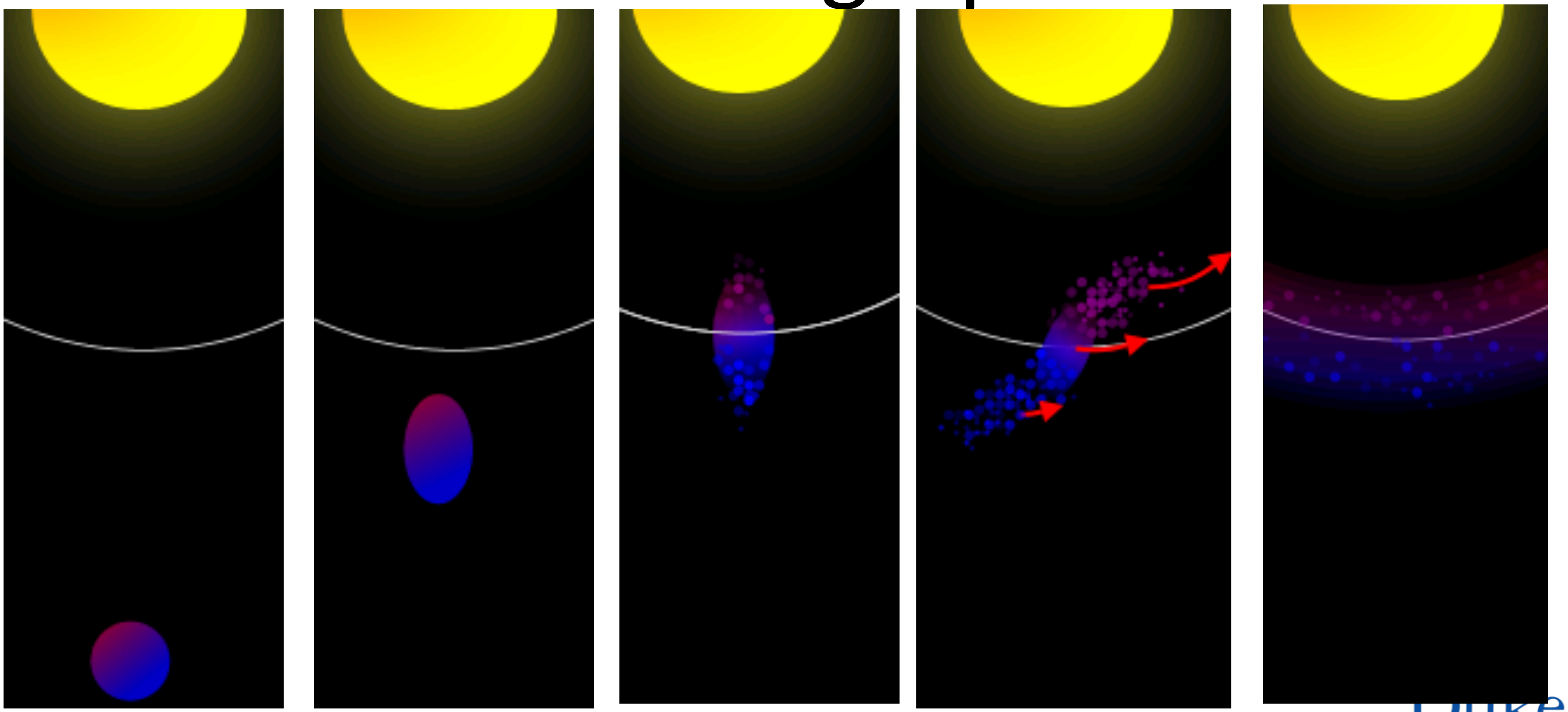
$$\frac{GM_m}{R_m^2} = \frac{2GM_pR_m}{D^3}$$

$$\frac{M_m}{R_m^3} = 2\frac{M_p}{R_p^3}\left(\frac{R_p}{D}\right)^3$$

$$D = R_p\left(\frac{2\rho_p}{\rho_m}\right)^{1/3}$$

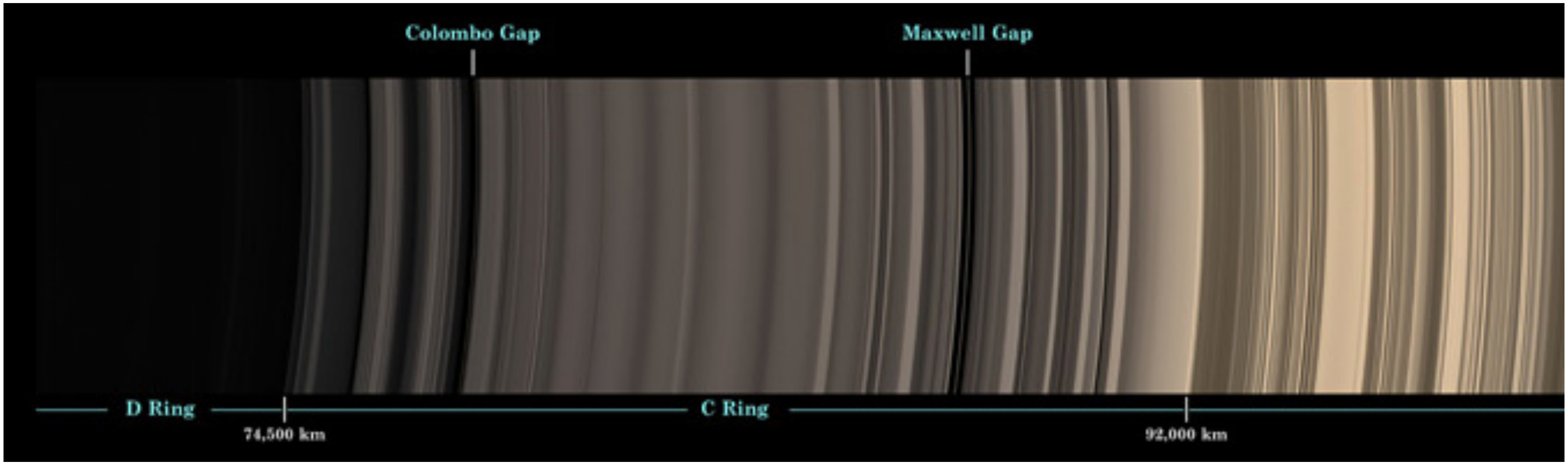
- Rings exist inside Roche Limit
- Small objects held together by chemical forces
- Gravitationally bound objects dispersed over time

Breaking Up



Ring Stability

- Shepherd Moons maintain gaps at resonant orbits
- Moons inside Roche Limit provide ring material



Credits

- Jupiter Globe: NASA/JPL/University of Arizona http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=9523
- Saturn HST: NASA/JPL/STSI http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=7903
- Uranus HST: NASA/Space Telescope Science Institute http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=10191
- Neptune HST: NASA Planetary Photojournal http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=2117
- Jovian Interiors: Lunar and Planetary Institute http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=166
- Jupiter Aurora: John T. Clarke (U. Michigan), ESA, NASA http://apod.nasa.gov/apod/ap001219.html
- Saturn Aurora: NASA/Hubble/Z. Levay and J. Clarke http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=3723
- Uranus Aurora: NASA, ESA, and L. Lamy (Observatory of Paris, CNRS, CNES) http://www.nasa.gov/mission_pages/hubble/science/uranus-aurora.html
- Jupiter Rings: NASA/JPL/Cornell University http://photojournal.jpl.nasa.gov/catalog/PIA01627
- Uranus Rings: NASA, Erich Karkoschka, University of Arizona http://hubblesite.org/gallery/album/solar_system/pr2004005a/
- Saturn Rings: NASA, ESA, E. Karkoschka (University of Arizona) http://hubblesite.org/gallery/album/solar_system/pr2004018b/
- Saturn Ring Mosaic: NASA/JPL/Space Science Institute http://photojournal.jpl.nasa.gov/catalog/PIA08389

Introductory Astronomy

Week 5: Solar System(s)

Clip 12: Asteroids and Comets

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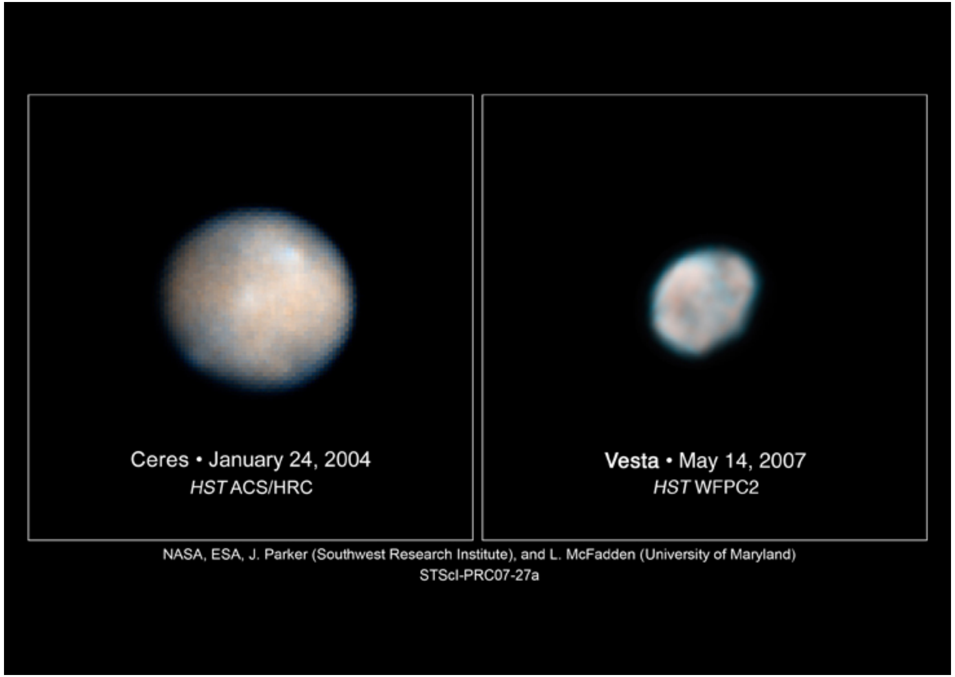
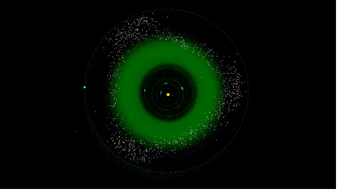
Asteroids

- Asteroids are planetesimals that never accreted to planets
- Most – but not all – never melted and differentiated so preserve chemistry of nebula on surface
- Some are debris of late collisions
- Some melted and are dwarf planets: in Solar orbit, big enough to melt, did not clear it's orbit

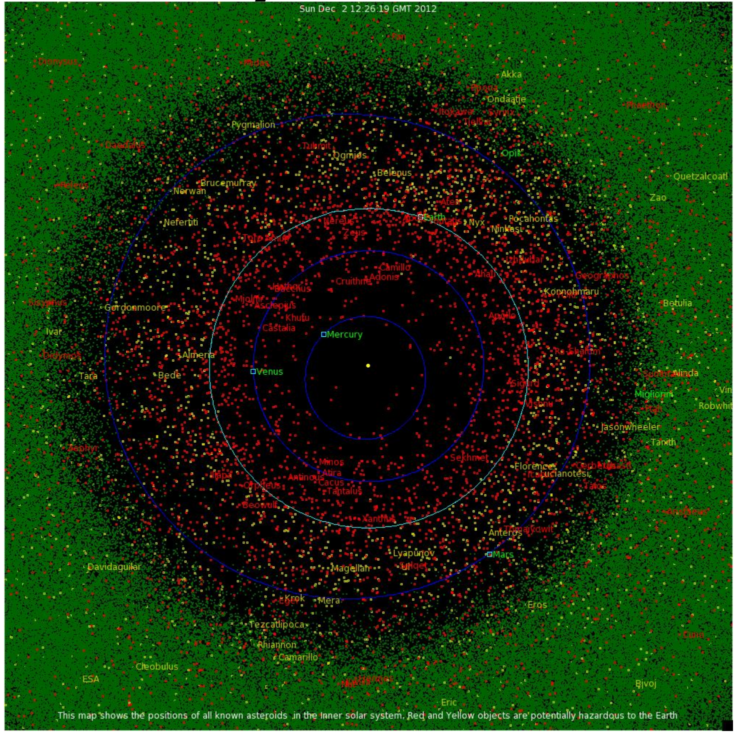


NASA, ESA, J. Parker (Southwest Research Institute), and L. McFadden (University of Maryland)
STScI-PRC07-27a



Where Are They?

- Most – in belt at 2-3.5AU
- Some in resonance with Jupiter
- Minor planets orbiting between Jupiter and Neptune are centaurs
- Some in Near Earth orbits or deflected near Earth
- Most meteors burn in atmosphere as shooting stars
- Surviving to ground makes a meteorite

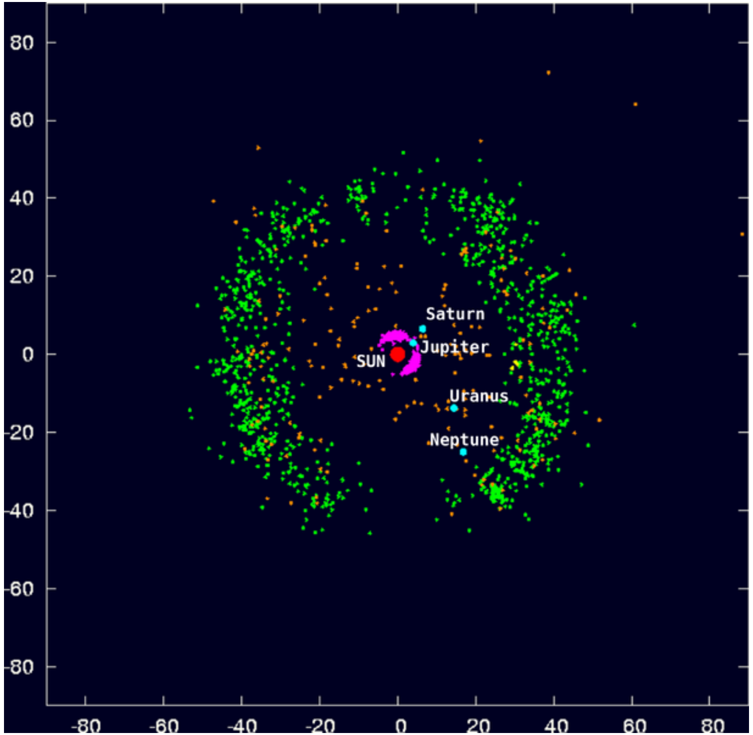


Sun Dec 2 12:26:19 GMT 2012

This map shows the positions of all known asteroids in the inner solar system. Red and Yellow objects are potentially hazardous to the Earth

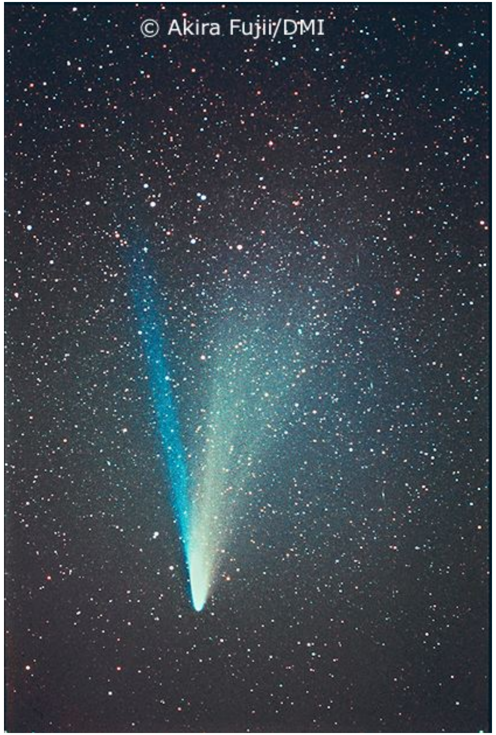
Farther Out

- Trans-Neptunian objects include Kuiper belt (Quaoar, Pluto, Makemake) at 30-50AU and moderate inclination
- Rich in Ices
- Over 1000 found
- From prevalence of short-period comets over 10^5 over 100km
- Long-period comets predict Oort cloud



Comets

- Collisions or effect of Neptune can slow these down into eccentric orbits taking them into inner Solar system
- Interaction with sunlight and Solar wind creates a comet
- Coma, Ion tail, Dust tail

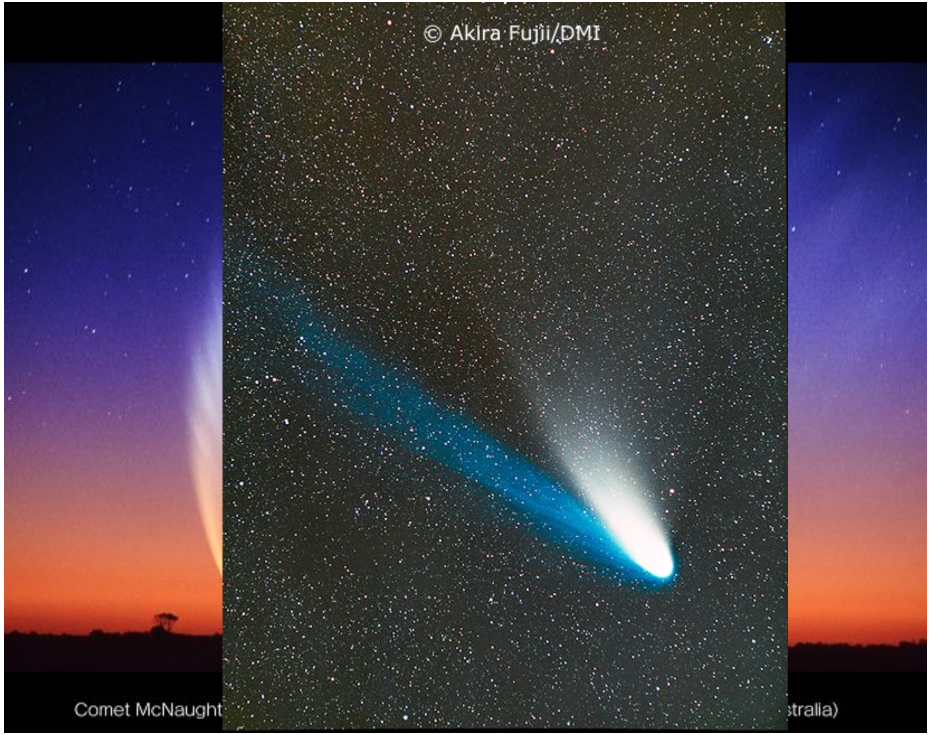

© Akira Fujii/DMI

Anatomy of a Comet

- Nucleus: original planetesimal. Dirty snowball??
- Sublimating volatiles carry away dust in jets
- Tenuous dusty atmosphere – coma – can be size of Sun and visible in Sunlight

Tale of Two Tails

- Dust and gas pushed by radiation pressure and Solar wind into tail pointing away from Sun
- Can be over 2AU long!
- Dust tail lags – arched – white in reflected Sunlight
- Ion tail governed by magnetic interaction with Solar wind – straight – glows blue



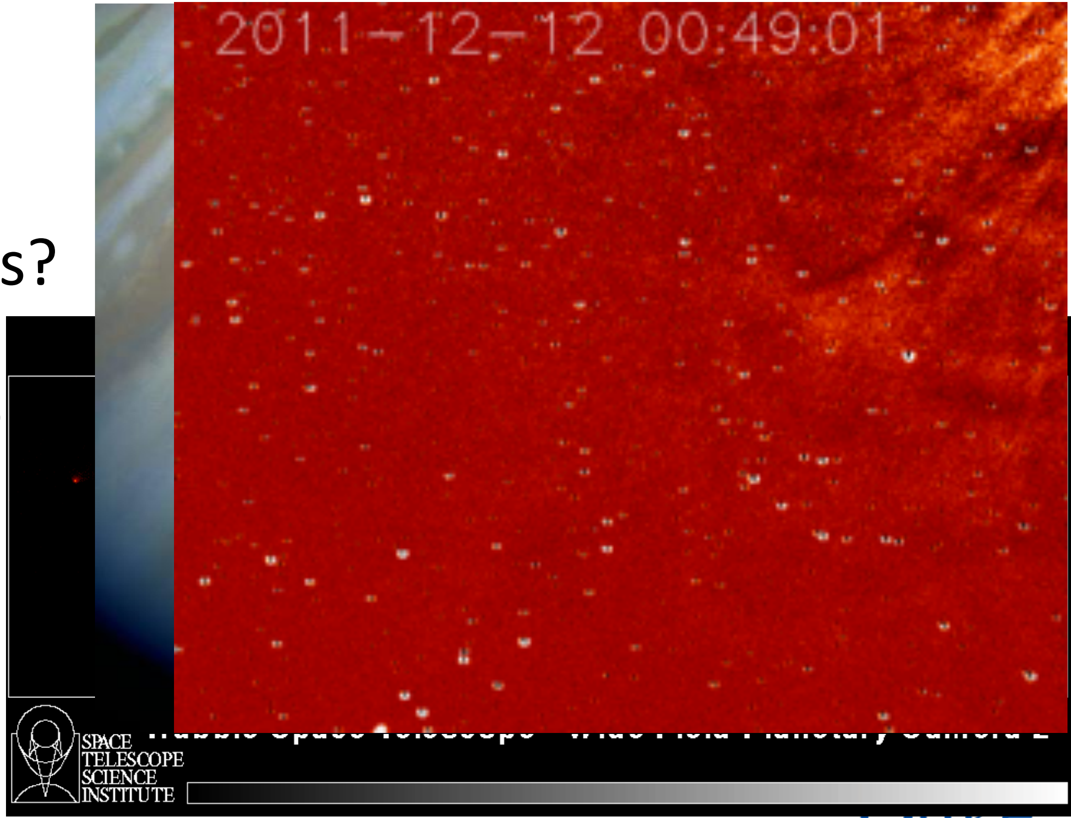
© Akira Fujii/DMI

Comet McNaught

stralia)

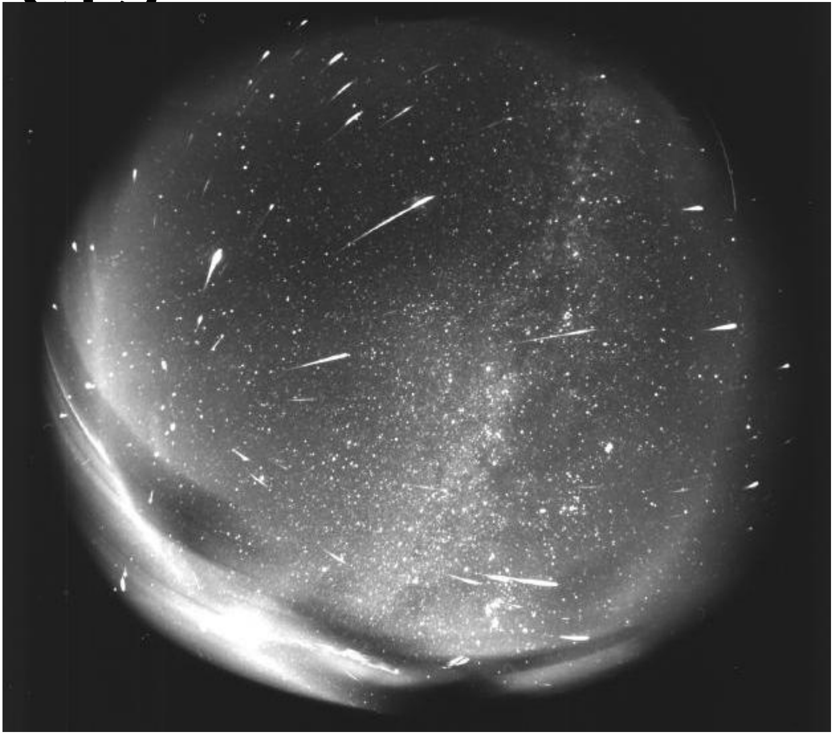
Comet's End?

- Ejection
- Extinction by loss of volatiles. Are some asteroids extinct comets?
- Disintegration with loss icy glue under recoil fro jets or tidal forces
- Collision with planet or Sun



Leftovers

- Every pass leaves debris in orbit
- Radial dispersion spreads debris along orbit
- If Earth encounters orbit – meter shower



Credits

- Asteroid PA8: NASA/JPL-Caltech http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=15204
- Ceres and Vesta: NASA/European Space Agency http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=9885
- Asteroid Map and Animations: S. Manley http://www.arm.ac.uk/neos/JupiterResonance/
- Comet West: Akira Fujii/DMI http://www.davidmalin.com/fujii/source/af12-04_72.html
- Comet Temple: NASA/JPS/UMD http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=4043
- Deep Impact: NASA/JPL-Caltech/UMD http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=9367
- Hartley 2: NASA/JPL-Caltech/UMD http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=11263
- Comet McNaught 2006: Akira Fujii/DMI http://www.davidmalin.com/fujii/source/af12-34.html
- Comet Hale-Bopp 1996: Akira Fujii/DMI http://www.davidmalin.com/fujii/source/af12-19_72.html
- Comet 73P: NASA, ESA, H. Weaver (JHU/APL), M. Mutchler and Z. Levay (STScI)/G. Rhemann and M. Jager http://hubblesite.org/newscenter/archive/releases/2006/18/image/a/
- Comet SL9: H.A. Weaver, T. E. Smith (Space Telescope Science Institute), and NASA http://www2.jpl.nasa.gov/sl9/image2.html
- Jupiter after SL9 Collision: Hubble Space Telescope Comet Team and NASA http://www.nasa.gov/centers/goddard/multimedia/largest/EduImageGallery.html
- Comet Lovejoy Encounter: NASA/STEREO/
- 2001 Leonid meteors: Juraj Toth (Comenius U. Bratislava), Modra Observatory http://apod.nasa.gov/apod/ap011104.html

Introductory Astronomy

Week 5: Solar System(s)

Clip 13: We May Not Be Alone

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Planets Elsewhere?

- Protoplanetary Disks and universality suggest many stars have planets
- First discovery in 1988. Now 853 around 672 stars
- Finding planets is tough: dim, small, near bright star. 32 planets in 28 systems detected by imaging

Who Orbits Whom?

- Planet and Star orbit common center of mass

$$M_p R_p = M_s R_s$$

$$R = R_s + R_p = R_s(1 + M_s/M_p)$$

$$R_s = (M_p/M)R$$

$$R_s = (M_{♃}/M_\odot) \cdot 7.79 \times 10^{12}\,\mathrm{m} = 7.44 \times 10^{9}\,\mathrm{m}$$

- One detection by Astrometry

How Fast?

$$\frac{GM_sM_p}{R^2} = \frac{M_sv_s^2}{R_s} \quad v_s^2 = \frac{GM_pR_s}{R^2} = \frac{GM}{R}\left(\frac{M_p}{M}\right)^2$$

$$v_s = \sqrt{\frac{GM}{R}}\left(\frac{M_p}{M}\right) = v_{\jupiter}(M_{\jupiter}/M_{\odot}) = 12.5\,\mathrm{m/s}$$

- 498 planet in 386 systems detected by radial velocity measurements

Transiting Planets

- If planet eclipses star can observe light curve
- Shape of curve helps find size, mass, even properties of atmosphere of planet
- 290 planets in 235 systems detected via transit
- Kepler has 2321 candidate planets in 1290 systems

Other Methods

- Gravitational lensing of starlight by planet. 16 planets in 15 systems
- Transit Timing Variation uses discrepancies in transit times of eclipsing planet to predict others in same system

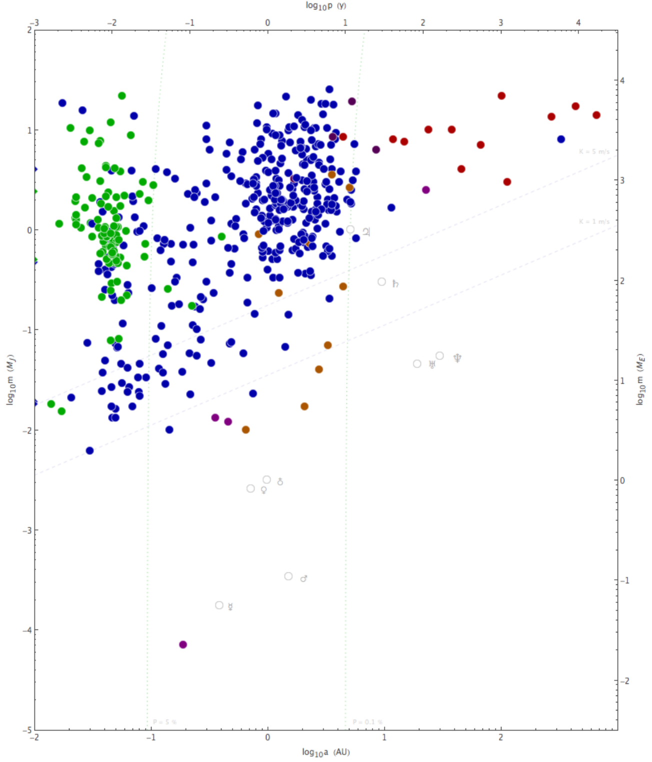
What Have We Found?

- 1-40% of (Sunlike) stars have planets. Planets are ubiquitous!
- Our methods are most sensitive to hot Jupiters so these are mostly what we find
- Migration is common as are strongly interacting orbits

Our Planet Hunting Neighborhood
Sun
Most of the planets found to date lie within about 300 light-years from our Sun.

What Are They Like?

- Taking selection bias into account, super Earths outnumber Jupiters
- Some SuperJupiters
- Kepler-16b orbits two stars



Summary

- Lots to learn in our own neighborhood
- Much of it being learned still
- Physics starting to pay off
- Exoplanets likely to revolutionize our understanding – Stay Tuned!

Credits

- Astronomy Animations: University of Nebraska-Lincoln Astronomy Education Group http://astro.unl.edu/
- Exoplanet Data: The Extrasolar Planets Encyclopedia, Jean Schneider, CNRS/LUTH - Paris Observatory http://exoplanet.eu/